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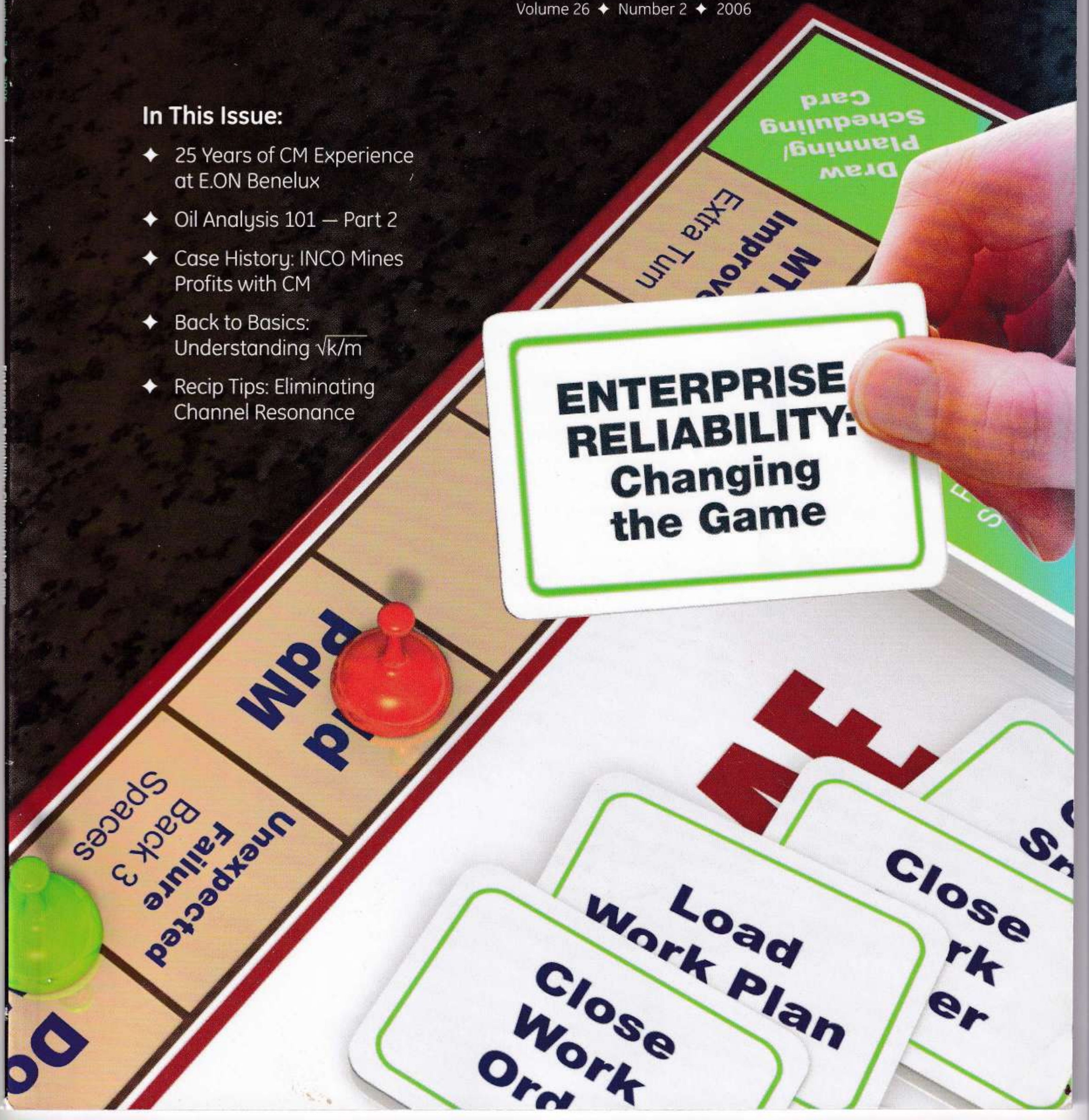

ENTERPRISE RELIABILITY: Changing the Game

Draw Planning/ Scheduling Card
Improve MT
Extra Turn
Unexpected Failure Back 3 Spaces
Load Work Plan
Close Work Ord
Close

Orbit

A Technical Publication for Advancing
the Practice of Operating Asset Condition
Monitoring, Diagnostics, and
Performance Optimization

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EDITOR'S NOTE

Welcome to our second issue of ORBIT for 2006. In my last note to you back in March, I suggested that we'd be supplementing the condition monitoring content of ORBIT with articles that discussed the broader topic of reliability. As I'm sure you noticed from the cover, we've done just that in this issue. MRG's Bob DiStefano and GE's Larry Covino have teamed up to write a very informative article on what reliability is and why it can be so powerful in transforming the operating results of a business.

You'll also find a closely related article that was submitted to us by E.ON Benelux, chronicling their reliability journey over the last 25 years. A significant part of that journey was migration from primarily time- and usage-based maintenance strategies to condition-based strategies. Although condition-based maintenance is merely one facet of an overall reliability program, it is a vital one and the article provides an excellent overview of not only the thought processes used in making the change, but the results E.ON has achieved along the way.

We round out the issue with several application articles that you'll likely find relevant. The first deals with the well-known rotor dynamic relationship between stiffness (k), mass (m), and the effect this has on a rotor's characteristic vibration frequency. John Winterton, one of our long-time machinery diagnostic engineers, contributed the article based on a recent job he completed for a customer where this principle was used to both diagnose and correct a problem. For our many readers interested in another condition monitoring technology—lubricant analysis—we're pleased to present part 2 of an article that appeared in our July 2005 issue of ORBIT titled "Oil Analysis 101." The contributor for the article is Dan Walsh of National Tribology Services, who has extensive experience in this field and is well qualified to comment on the practical aspects of establishing and sustaining a successful lubricant analysis program as part of your condition monitoring activities.

Finally, you'll find a case history from one of our customers in Canada, Inco Ltd. It summarizes their experiences with vibration monitoring on some of their critical mining equipment. The article underscores an important aspect of condition monitoring that we can never repeat too often: the need for dynamic and transient data, not just static trend data.

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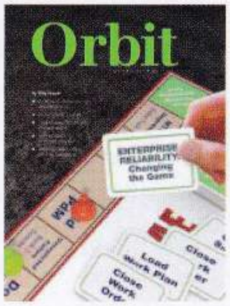

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Compelling Reasons for Change

In the past, maintenance work on turbines and generators occurred practically without exception based upon the machinery OEM's recommendations. While very easy to plan maintenance using this method, it is also extremely expensive. OEM maintenance recommendations are generally determined in a manner that allows them to be used universally, meaning they apply to assets that have been operated under the most aggressive conditions as well as those run under ideal conditions, leaving little room for the unique operating circumstances that may apply to each asset. In addition, the revenue from replacement parts and maintenance services have also been strong incentives for machinery OEMs to encourage customers to rely upon their recommended maintenance intervals and activities.

Compounding these forces, the operators of turbine generators are not specifically in the business of machinery maintenance—they are in the business of supplying power—and may therefore lack the specific technical know-how that the machinery OEM possesses. Also, the absence of competition within the power supply sector in the past meant that costs could simply be passed along to consumers. Combined, these forces led operators such as E.ON Benelux to adhere to the OEM's prescribed maintenance intervals without question. This resulted in our turbines and generators being opened quite frequently for inspection and revision.

However, this strategy was, as noted previously, very costly and inefficient for the following reasons:

- Machinery that is functioning properly is opened (unnecessarily) for inspection.
- Machinery components that are well worn in and functioning perfectly are replaced simply because they have reached the interval recommended by the OEM rather than actual condition assessment of the component.

Table 1 – Summary of E.ON Benelux Facilities in South Holland

Plant	Output	Fuel	Machinery
Maasvlakte	Elec: 1050 MW	Coal	2 - 525 MW steam turbine generators
Leiden	Elec: 85 MW Heat: 60 MW	Natural Gas	1 - 25 MW steam turbine generator 2 - 30 MW aeroderivative gas turbine generators
The Hague	Elec: 78 MW Heat: 60 MW	Natural Gas	1 - 26 MW steam turbine generator 2 - 26 MW aeroderivative gas turbines
RoCa 1	Elec: 24 MW Heat: 85 MW	Natural Gas	1 - 24 MW industrial gas turbine generator
RoCa 2	Elec: 24 MW Heat: 85 MW	Natural Gas	1 - 24 MW industrial gas turbine generator
RoCa 3	Elec: 220 MW Heat: 200 MW	Natural Gas	1 - 125 MW industrial gas turbine generator 1 - 95 MW steam turbine generator
Delft	Elec: 93 MW	Natural Gas	4 - 24 MW industrial gas turbine generators
Galileïstraat	Elec: 209 MW Heat: 256 MW	Natural Gas	1 - 77 MW Steam turbine generator 3 - 44 MW industrial gas turbine generators

- Additional perfectly functioning parts are replaced even though they have not yet reached their recommended replacement interval simply because the machine is open and waiting until the next planned outage would exceed the recommended interval.
- Errors often occurred during disassembly or assembly, introducing problems where none existed previously.
- New parts have a higher probability of failure (so-called "infant mortality") than parts that are already functioning properly
- Wearing in of replacement parts can introduce operating constraints

In summary, this calendar-based approach to maintenance can actually have the unintended effect of reducing machinery reliability and availability, not to mention the additional maintenance costs it incurs.

A Better Approach – Condition Monitoring

In the early 1980s, we began to realize that technologies allowing us to assess the actual condition of our machinery were becoming quite sophisticated—and that this capability could have a large influence on both the maintenance work performed and the corresponding availability of our units. Basically, by accurately determining the condition, the right maintenance could be carried out at the right time, thereby avoiding unnecessary work and risks. As such, we began investing in both the manpower and equipment that would allow us to accurately assess the condition of the machine fleet and consequently to determine and plan, on the basis of this condition, the necessary maintenance activities.

We further understood that condition-based approaches could be divided into the following two broad categories:

Condition Monitoring (CM). The use of *measurement* technologies to determine the condition of an asset while it is operating.

Condition Inspection. The use of *inspection* techniques to determine condition; specifically, those techniques that require no (or very little) machine disassembly and are minimally disruptive to operations.

However, while we knew that condition-dependent approaches held great promise, it was equally clear that failure-dependent and usage-dependent approaches would continue to have a place in our overall maintenance program. To help us decide what approach to use for each asset and failure, we devised the following attributes/questions (Table 2) and corresponding flowchart (Figure 1).

Table 2 – Key Questions

Attribute	Question
Mechanism of failure	What will cause the failure?
Probability of failure	What is the likelihood the failure will occur?
Effects of failure	Are there serious consequences to the failure?
Symptoms of failure	Can the failure be predicted?
Mitigation of failure	Can the failure be prevented (such as through modification)?

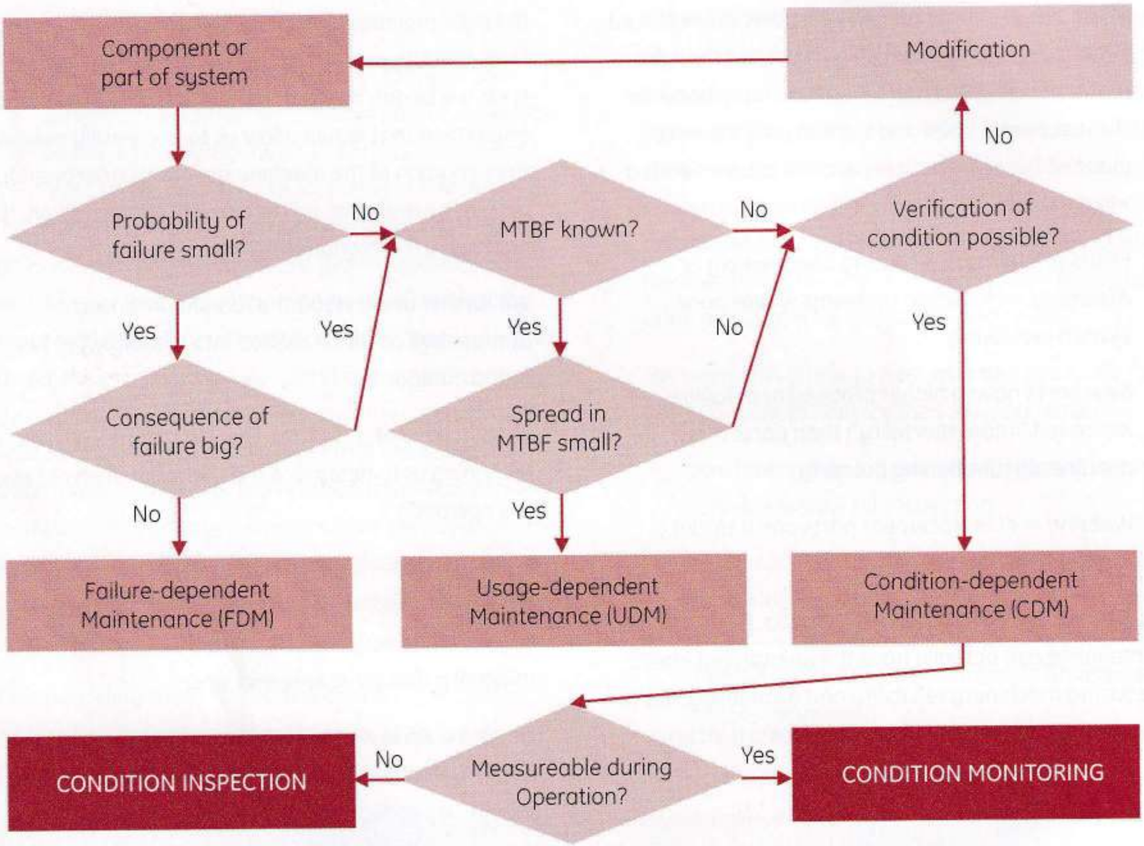

Component or part of system
Modification
Probability of failure small?
MTBF known?
Verification of condition possible?
No
No
No
Yes
Yes
Yes
No
Yes
Consequence of failure big?
Spread in MTBF small?
No
Yes
Failure-dependent Maintenance (FDM)
Usage-dependent Maintenance (UDM)
Condition-dependent Maintenance (CDM)
CONDITION INSPECTION
No
Measureable during Operation?
Yes
CONDITION MONITORING

Figure 1 – **Flowchart for determining an appropriate maintenance approach.**

In words, the flowchart can be summarized as follows:

- When the consequences of failure and probability of failure are low, use failure-dependent maintenance (fix it when it breaks).
- When the Mean Time Between Failure (MTBF) is known and the variance in MTBF is small, use usage-dependent maintenance (fix it based on running hours or calendar intervals)
- In all other cases, if verification of condition is technically feasible, use this approach. If not, modify the component to prevent or lessen failures.

Goals of Condition Monitoring

The aim of the CDM philosophy is simple: to increase the availability of a component or asset at lower costs and with manageable risk. As will be shown, E.ON Benelux has successfully employed the CDM approach to achieve this. We have lengthened maintenance intervals, particularly in the case of our steam turbines and generators, and we have lowered the percentage of time during which the machinery is not available. An additional advantage has been that even when an unforeseen calamity occurs, the historical data collected by our condition monitoring

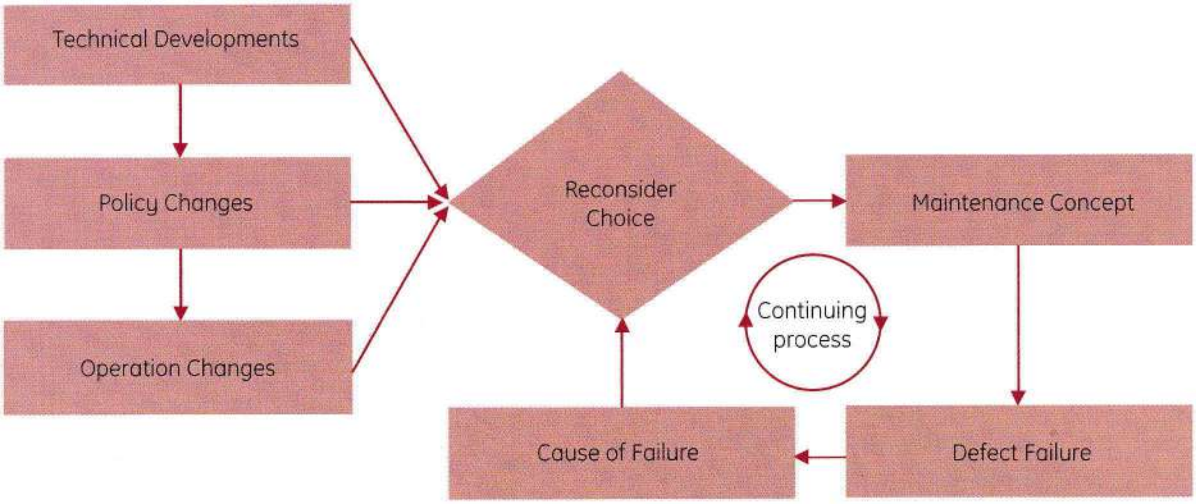


Figure 2 – **The choice of a particular maintenance approach should be continually reassessed in light of changing policies, operating conditions, and technical developments.**

systems provides us with much better insight into the behavior of our machines, enabling extremely goal-oriented repair or maintenance work to be carried out, because the nature, location, and severity of the failure can often be determined before the machine is opened.

While the potential to lower costs through a CDM-based approach to maintenance will be appealing to operators, the second aspect of the CDM philosophy is equally important: manageable risk. For example, those who insure machinery and plants will be keenly interested in understanding the risk associated with deviating from the machinery OEM's recommendations or approach in favor of a CDM approach. Their primary concern will not be the plant's maintenance costs, but the risk that a particular maintenance approach incurs.

When to change an approach

The choice of a particular maintenance approach for a specific machine should not be permanent. For example, the way in which a machine is used or operated may change over time, such as conversion from primarily a peaking unit to a base-load unit, which may dictate a very different maintenance approach. Policy changes may likewise dictate a change; for example, more stringent penalties on certain types of failures, such as those that cause unwanted environmental emissions, would impact the consequences of failure. Or, technical developments may allow a design modification that prevents a failure, lessening the need for condition monitoring. Figure 2 illustrates this idea of a "feedback loop" for assessing the ongoing suitability of a particular maintenance approach for an asset or component.

Development of CDM at E.ON Benelux

CDM is not a single measurement type or technology. Rather, it is a collection of measurements and technologies that collectively give insight into the condition of the machine. Examples include:

- Vibration measurements
- Expansion measurements
- Water analysis
- Process parameters
- Foundation height measurements
- Lubricant analysis
- Strain gage measurements
- Efficiency measurements
- Electric measurements (insulation integrity, etc.)
- Non-destructive investigation

Nor is condition monitoring as simple as making the above measurements and comparing to some absolute standard. While this is occasionally possible, it is more frequently the case that a relative assessment must be carried out, using trend data to establish "normal" versus "abnormal" and "acceptable" versus "unacceptable." Figure 3 illustrates this procedure. If a deviation from a pertinent standard or previous condition measurements is observed, a diagnosis must be made to determine the cause of this deviation. Once determined, the condition measurement can be continued.

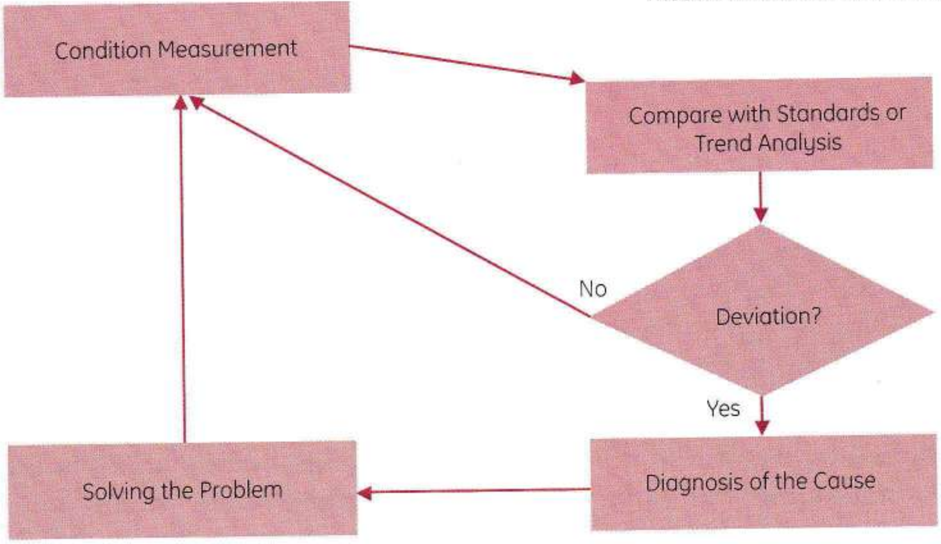


Figure 3 – **Condition monitoring is more than just collecting the right data. To be effective, it requires the data to be interpreted whenever there is a deviation from "normal."**

The Role of Vibration Monitoring

In our own experience, the roles of non-destructive investigation and vibration monitoring have been particularly important. In this article, however, we focus primarily on our vibration monitoring experiences.

In the past, even though all turbine generator systems were equipped with continuous vibration measurement systems, vibration was treated more as a "protective " (i.e., machine trip) function than as a tool for assessing condition. Our very first steps into condition monitoring occurred around 1980 when we began manually recording the vibration levels on the machinery bearing housings and manually transcribing these values onto trend graphs. Later, we began using a real-time analyzer to isolate and trend individual frequency components within the vibration spectrum. From these simple beginnings, we began bringing specialized employees together in workgroups and workshops from various locations to look more closely at the possibilities of vibration analysis as a condition monitoring tool.

During the mid 1980s, we began fitting our machines with relative vibration transducers (i.e., proximity probes), allowing us to directly observe the shaft, and greatly increasing our capabilities for assessing condition. We also made a practice of installing X-Y transducer pairs, rather than a single probe, allowing us to determine shaft position (orbit and shaft centerline) within the bearings or glands.

It was during this period that we also began taking so-called "run down" (or transient) measurements, documenting the vibration of the unit at specified rpm intervals as it decelerated from running speed to a stop. We relied heavily on Bodé diagrams, allowing us to assess rotor dynamic resonances (critical speeds), amplification factors, damping, and structural resonances, among other things. Shaft position measurements were also helpful to us, allowing an assessment of the alignment conditions of the machine during both running (hot) and stopped (cold) conditions. However, in those days, it took approximately three days to set up for such "run down" measurements, aided by a local vibration measurement and analysis company.

By the end of the 1980s, our expertise in CM had grown to the point that a separate Maintenance Diagnostics team had been formed. We provided machinery diagnostic services for both our own network of plants as well as third parties. At this time, we began fitting all of our turbine-generator installations with online, computerized condition monitoring systems. The benefit of such systems is that data is collected automatically, both during transient and steady-state operating conditions. They also capture "event" information, such as surrounding a vibration alarm or process upset.

"BY THE END OF THE 1980S, OUR EXPERTISE IN CM HAD GROWN TO THE POINT THAT A SEPARATE MAINTENANCE DIAGNOSTICS TEAM HAD BEEN FORMED."

Initially, we installed systems from several different suppliers, all of which were responsible for various "machine saves" and helped confirm the value of condition-based monitoring to both our management and ourselves. However, today virtually all of our online installations are based upon Bently Nevada™ 3500 series monitoring systems and System 1® software. For those machines not fitted with online systems, a Bently Nevada™ ADRE® system is used to collect data as required, such as during a planned shutdown or when the machine is exhibiting problems.

Case Histories

As previously mentioned, we have used online condition monitoring systems from a variety of manufacturers over the years. As such, the case histories presented here reflect several different systems. However, the intent of this article is not to highlight the merits or shortcomings of a particular manufacturer's systems; rather, it is on the merits of condition monitoring itself, regardless of the system chosen so long as it is capable of certain functionality, such as the ability to capture transient data and display certain types of plots. The following illustrate the value of such systems in a variety of scenarios.

Case History 1 Galileïstraat Unit A

This particular case history was chosen because it represents one of our very first successes with CM, and was the first time we used CM to avoid opening a machine for regularly scheduled maintenance. The unit is a 160MW steam turbine, built in 1967 and retired from service in 1992. The last time the unit was opened for inspection was in 1977, after 51,000 running hours and 130 starts. During that 1977 outage, updated vibration instrumentation was installed, and once the unit was restarted, we began trending vibration and process data, augmenting the water and oil quality data that we had already been trending. The next scheduled outage for the machine was to have been in 1988, 45,000 operating hours and 720 starts later. However, based upon stable vibration and efficiency trends we had observed for the previous eight years, and after consultation with the machinery breakdown insurer, we elected to forego the usual complete outage, opening, and inspection of HP, IP, and LP sections. Instead, we merely removed the generator shields to examine the winding ends and perform a global internal generator inspection. The unit was then returned to service following this "mini" outage and it continued to operate for another 15,000 operating hours and 250 starts until it was permanently retired from service in 1992.

One noteworthy vibration problem did occur on this unit between 1988 and 1992, and we again used CM to diagnose and address the root cause, with the need for a more extensive outage. We began to observe unstable vibration trends; they were particularly erratic from one start to the next. Expansion measurements over the length of the machine were also made, but did not show any significant deviations. However, radial expansion measurements between the bearing housing and turbine casing did show deviations. In other words, the positions of the turbine casings and bearing housings were not maintaining their correct alignments relative to one another as the machine heated and expanded. We found that due to fretting, a number of wedges that should normally allow unhindered expansion were jammed. This was causing the bearing to be pushed out of its position relative to the turbine casing, creating abnormal preloads on the shaft. This manifest as rubs between the shaft and the gland seals, increasing the vibrations.

We remedied the situation by treating and hardening the wedges, and by executing regular checks on the transverse expansion to ensure it was not hindered. This use of CM to avoid a much larger outage and to solve an expansion problem yielded savings of 840,000 USD. It also increased the availability of the unit by 10% over the 15-year period from 1977 to 1992.

Case History 2 Waalhaven Unit 4

Units 4 and 5 at the Waalhaven plant in Rotterdam are both 340 MW steam turbine - generator sets. The units were put into operation in 1974/1975 and were augmented with gas turbines as part of a combined cycle upgrade in 1986. Partly due to recurring vibration problems, the units were equipped with an online vibration diagnostics system in 1992. One aspect of this system that we found highly useful was its ability to allow individual 1X acceptance region alarms for various machine loads. Acceptance region trending and alarming is highly useful for detecting malfunctions such as

(continued on page 14)

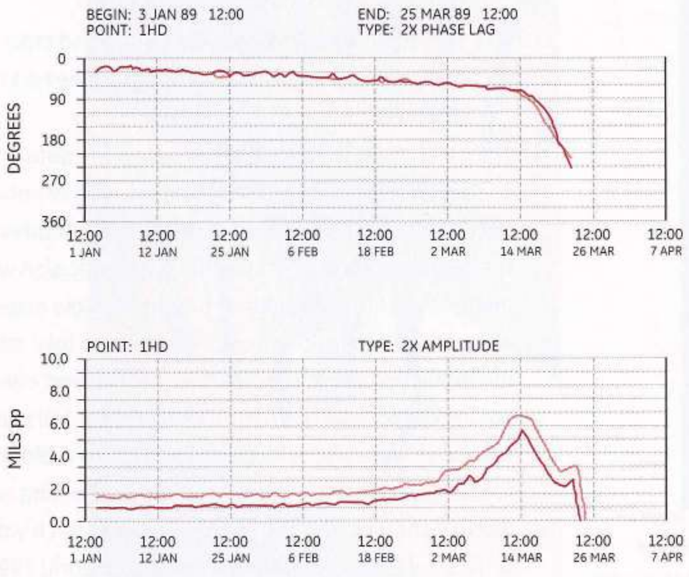
The Usefulness of Acceptance Regions

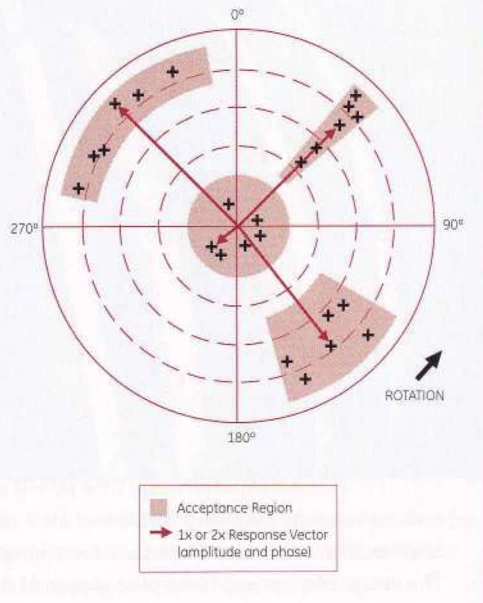
When vibration is filtered to a specific multiple of running speed (such as 1X), it can be characterized as a vector. When this vector is trended over time, this is known as an Amplitude/Phase/Time (APHT) plot. As shown below, the APHT plot can be represented in either cartesian or polar coordinates. When using Cartesian coordinates, it resembles (and can be easily mistaken for) a Bodé diagram; however, unlike the Bodé diagram, an APHT has as its X-axis units of time rather than machine speed. Similarly, when graphed using polar coordinates, an APHT resembles a polar plot. However, the polar plot is used to show vibration vector changes as a function of machine speed. In contrast, the polar APHT shows vibration vector changes as a function of time—not rpm.

There is a tendency by some—particularly novice vibration analysts—to be concerned only with increases in vibration amplitude. More skilled practitioners, however, understand that it is really change in vibration that should always be the basis for concern, and this can be represented by either a change in magnitude or a change in phase—both can be equally indicative of a serious malfunction.

For this reason, alarming strategies that can detect abnormal changes in the vibration vector (not just an increase in its magnitude) are highly valuable. GE pioneered the concept of an "acceptance region" in its Bently Nevada™ instrumentation beginning in the late 1980s. Simple in concept, but highly useful in practice, the Acceptance Region is simply a defined region within the polar APHT for which the vibration vector is considered normal. When the vector goes outside this defined region, it represents an abnormality and an alarm is generated. Because the polar APHT plot is the most convenient way to visualize and establish acceptance region alarms, it is often referred to as an Acceptance Region plot.

Acceptance region alarming schemes have steadily increased in sophistication over the last 15 years. Systems today are available that can switch between multiple acceptance regions based on certain machine operating states, such as differing load conditions.

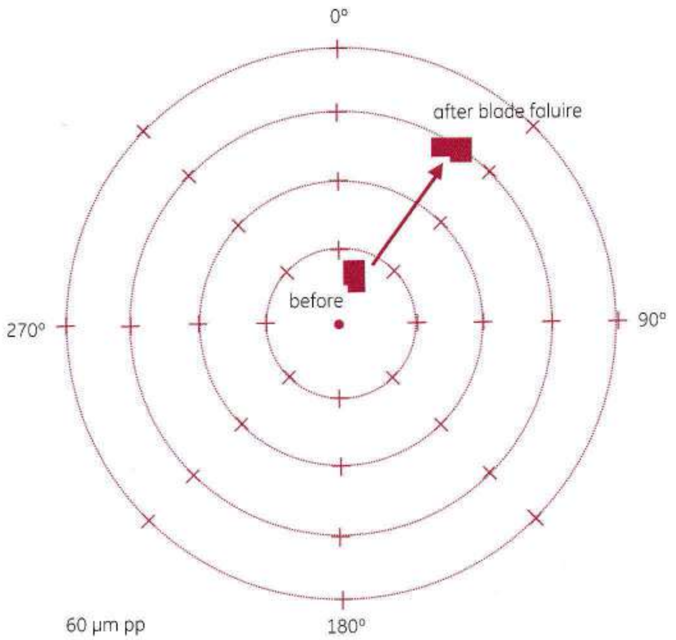




The APHT plot in cartesian coordinate format (above) resembles a Bodé plot. The APHT plot in polar coordinate format (right) resembles a Polar plot. Note the ease with which amplitude and phase "acceptance regions" can be visualized in polar format, leading to the plot at right being commonly referred to as an Acceptance Region plot.

imbalance, shaft cracks, shaft bows, and shaft preloads (see sidebar on preceding page).

On February 6, 1996, the system detected a very rapid change in the 1X vector on the front bearing of the IP turbine. As shown in Figure 4, the cluster of 1X vector trend points jumped from 10 µm to 45 µm with a slight phase change. We instructed operations to make changes to both real and reactive loads; however, neither increasing nor decreasing load affected this "new" 1X vibration vector appreciably.



Date:	Feb 6, 1996
Time:	18:8:21
Speed:	3000
MW:	245
Mvar:	-2

Figure 4 – **Amplitude/Phase/Time (APHT) plot from IP turbine bearing 1, showing before and after clusters of trend points with dramatic and sudden change of 1X vector. The vector change was more pronounced at #1 (front) rather than #2 (rear) bearing, suggesting the malfunction location was closer to the front bearing than the rear.**

A few hours after this incident, the unit was taken out of operation, according to plan. During the coast-down of the unit, the online system collected transient run-down data. This data was overlaid with previously collected transient data from several other shutdowns from just a few weeks prior. As shown in the Bodé diagram of Figure 5, there was a spectacular change.

The team analyzed numerous facets of the data from all machine train bearings along with previously acquired inspection data as follows:

- The Bodé plot showed a much larger amplitude response, but no significant change in resonant frequency.
- The IP turbine rotor was known to be quite sensitive to imbalance based on previous balancing experiences.
- The mode shape of the IP turbine rotor had changed.
- The 1X vector showed a rapid, sudden change and was most pronounced at the front bearing of the IP turbine.
- During an earlier inspection, pitting and cracking of blades on the #6 row of the IP turbine had been observed.

The most obvious conclusion based on the data was a sudden change in the amount and location of imbalance, caused by a loss of blading and/or shrouding in the IP turbine section. That same day, a decision was made to partially open the IP turbine to allow inspection of row #6. Preparations were also made to take stock of the repair options and to develop alternatives, carried out in collaboration with the machine OEM. Various scenarios were discussed, ranging from new blades, to blades repairs, to removal of blades. Affecting our discussions was also the knowledge that Unit 4 was scheduled to be removed from service in early 1997. Ten days after the 1X vibration vector alarms had occurred, Unit 4 was partially opened and, as expected, missing blade and shrouding material on row #6 was observed (see Figure 6).

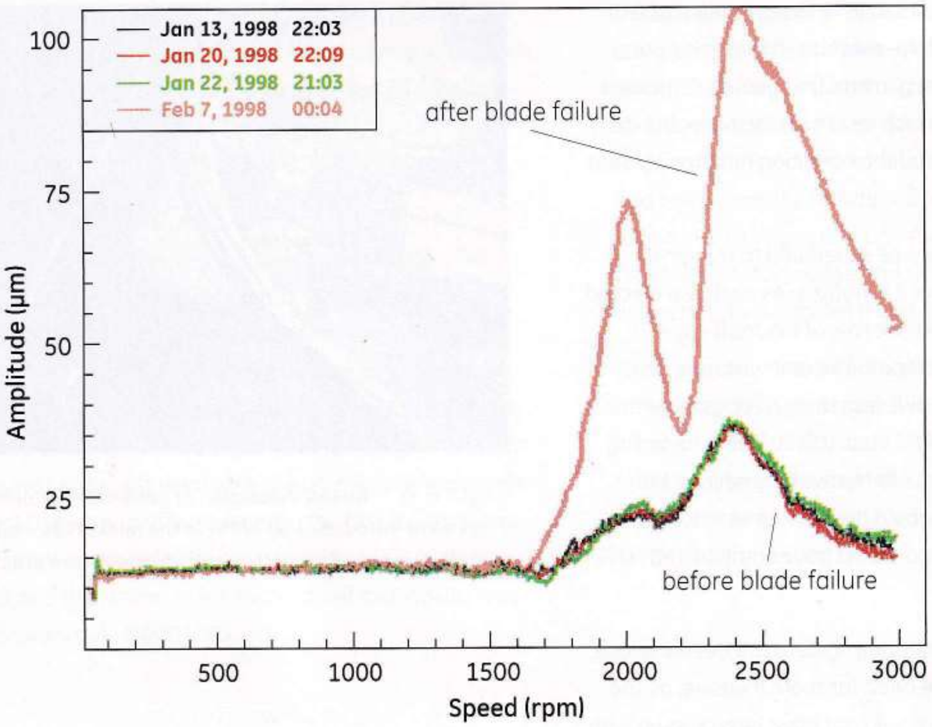


Figure 5 – **Bodé diagram from IP turbine front bearing showing overlaid data collected prior to and after 1X vector change of Figure 4.**

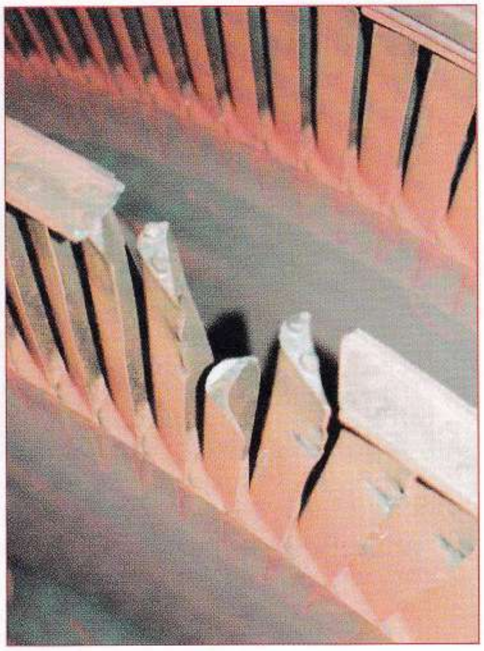


Figure 6 – **Inspection confirmed the loss of blading and shrouding on row #6 of the IP turbine.**

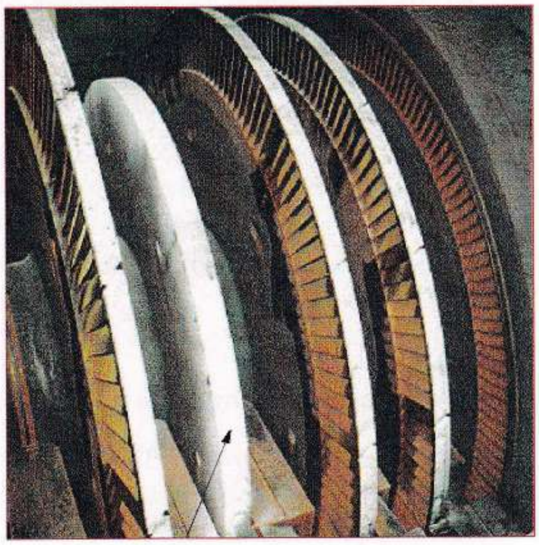


Figure 7 – **Row #6 was subsequently removed by grinding, since the machine was slated to remain in service for only another 12 months.**

Because the team was able to very narrowly pinpoint the suspect portion of the machine, the interior parts of the IP turbine (inner cylinders and glands) remained closed, resulting in a much less invasive inspection than would have incurred had the condition monitoring data not been available.

As mentioned, the unit was scheduled to remain in service for only another 12 months. As such, we elected to simply remove the entire row of blades (Figure 7), rather than replace or repair. The unit was returned to service on Feb 26, 1996, less than 20 days after the blades broke. The "repair" cost 100,000 USD, including 200 man-days of labor. Alternatively, renewing the entire blade cascade would have taken at least four months to complete and would have come to 1MM USD, including fines.

Had the condition monitoring system not been in place, the outage would have been far more invasive, as the source of the problem would not have been known with nearly as much precision. It is also likely that additional damage may have ensued, affecting other blade rows, rather than confining the damage to only a single row. While the removal of row #6 resulted in a 1% overall decrease in turbine efficiency, 3MW loss of power, and 100,000 USD in additional fuel costs for the remainder of its service life, this was more than offset by the savings realized by removing rather than repairing/replacing the blade cascade.

Case History 3 Maasvlakte Units 1 and 2

Maasvlakte consists of two 525 MW steam turbine units, put into service in 1975. Initially, the plant used gas-fired boilers. Later, between 1984 and 1987, the plant was retrofit at a cost of 900MM USD with coal-fired boilers, each with two fly ash filters and two flue gas desulphurisation systems. During this conversion, the turbines were systematically inspected, isolating weak spots and modernized with the latest technology [3].

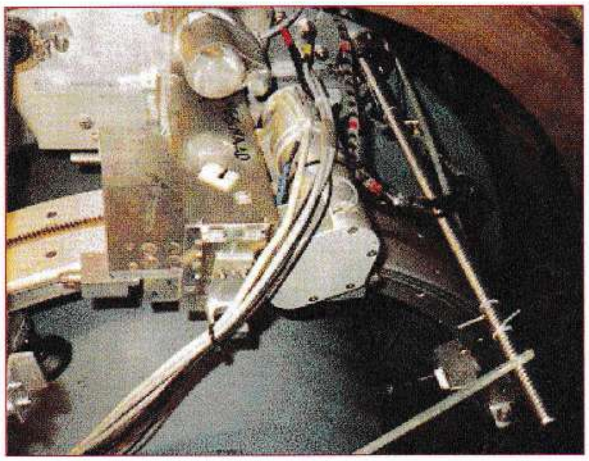


Figure 8 – **In-situ inspection of generator retaining rings were introduced by KEMA in the mid-1990s, making a condition-based maintenance approach more practical.**

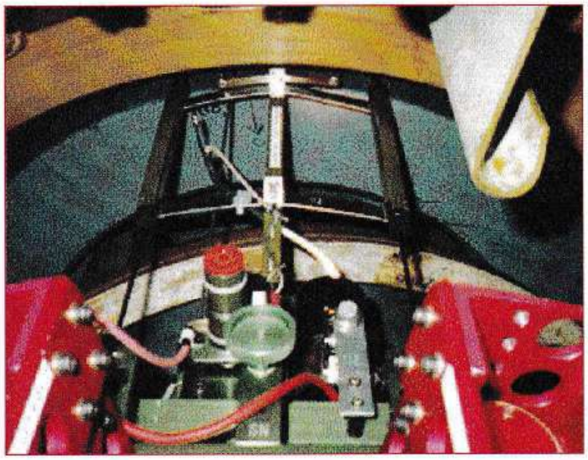


Figure 9 – **At about the same time, ABB introduced in-situ inspection technology for assessing the condition of stator wedges, as shown in this photo.**

The machines each consist of an HP, IP, and three LP sections. After conversion, two large overhauls on each unit were planned for the 25 years of remaining life anticipated for the plant.

During a visit to German power plant using similar turbine-generators as those at Maasvlakte, we learned that their machines had only been opened for the first time after 15 years of service [2]. We thus initiated research into the possibility of extending our own outage intervals on the machines by replacing two large, planned outages per machine with a single outage per machine at the half-way mark of their 25-year lifespan. This was superimposed with the premium/fine arrangement that was in effect whereby the fine for each day the plant is unavailable was approximately 60,000 USD and the premium for each day of availability was approximately 8,000 USD.

Using the flowchart of Figure 2, we analyzed the critical components of the turbine-generators [1], [4] and concluded that the condition of these components could, for the most part, be assessed via condition monitoring and in-situ inspection. Additionally, new technologies had been recently introduced at that time, allowing us to use in-situ inspection and non-destructive testing in assessing stator wedge and retaining ring condition in our generators (Figures 8 and 9).

We also gave careful considerations to blading. Steam turbine blades are designed, in principle, to last for the life span of the unit. Should a blade break anyway (refer to case history #2 above), this can be detected by condition monitoring, after which an effective decision can be made and the resulting damage minimized.

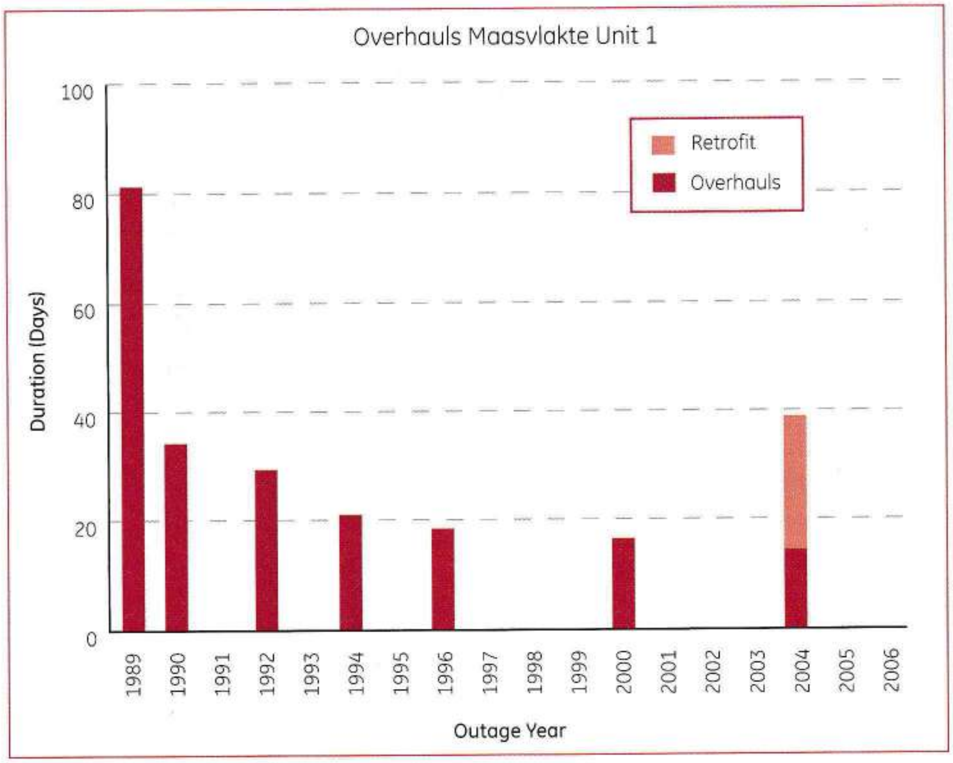


Figure 10 – **The frequency and duration of overhauls on this unit have continually decreased as a result condition-based maintenance strategies.**

Experience shows that indications of cracks in blades, such as from low- or high-cycle fatigue or pitting corrosion, will develop relatively quickly. The blade will then either break or failure progression will plateau. As such, the risk of a blade failure is not considerably reduced by, for example, adhering to the prescribed 50,000 hour inspection for these units. Further experience shows that a blade failure in the turbine often causes little damage to the rest of the turbine, with the notable exception of the last row of the LP turbine – which is why we inspect the LP blades every 2-3 years. Also, because our experience has shown that blade breakage in the IP and HP sections are usually preceded by pitting corrosion, we place considerable emphasis on excellent steam/water quality, since this is generally the root cause of pitting/corrosion problems.

On this basis, a selective turbine overhaul schedule was developed, calling for the turbine HP and IP sections to be opened only once during their lifetime. In the interim —during boiler inspections—the first and last rows of these turbines are inspected in-situ by means of an endoscope. Of the three LP turbines on each unit, each is opened only once every 9 years (each is staggered at 3 year intervals), and without removing the rotor. In the case of the last row of LP turbine blades, random testing and inspections are conducted for blades and their fastenings, looking for corrosion cracking. The condition of the particular LP case opened every three years is considered representative of the others. If no problems are found, we assume the others are intact as well.

The critical parts of the generator are inspected on location with the rotor in-situ, using the technologies of Figures 8 and 9. Both the retaining rings and the stator wedges are investigated with an automated system. In addition, the insulation condition is measured and the cooling and H_2 systems are continuously monitored. The decision to leave the heavy generator and LP rotors in situ during inspection means that time-consuming balance work after the overhaul is prevented.

As a result, we abandoned the idea of complete turbine-generator overhauls in 1994. The duration of overhauls was dramatically shortened, due to the reduced scope of an outage, shrinking from the 12 weeks of the past to just three or four weeks. The machine breakdown insurer was consulted and has approved this revised approach, which relies more heavily on condition monitoring than on conventional major outages at shorter intervals.

At the time this planning was conducted in 1994, the expected net benefit by reduction in number, scope, and duration of planned outages was 8.4MM USD in overhaul costs and approximately 20MM USD in premiums/fines. This was based on a net cash value calculation from 1994 to 2005 at a 4% interest rate. We also envisioned our non-availability would be reduced by 50%, going from 7% to 3.5%.

As we now look back on these 1994 estimates, our actual results have been even better than expected. The number of overhauls decreased as planned. Also, as shown in figure 10, the duration of the overhauls were shortened with each successive outage. In 2004, Unit 1 was retrofit as part of a life extension program. This will extend the life of the unit to 2023 and required extra outage time to address the turbines, generator, and control systems with upgraded components. A similar retrofit is planned for Unit 2 in 2006/2007.

Case History 4 ROCA CO_2 compressor

At our Roca plant in Rotterdam, a specially tuned boiler supplies carbon dioxide (CO_2) to nearby greenhouses, accelerating the growth of vegetables. The plants in the greenhouses convert the CO_2 back into oxygen.

The CO_2 is piped to these greenhouses by means of a steam-turbine-driven 12MW radial compressor. The CO_2 boiler, together with a waste heat boiler fed by a gas turbine, produces steam to drive a steam turbine. Both the gas- and steam turbine drive generators to produce electricity. Extraction stream is used for district and greenhouse heating. The main part of the electricity is delivered to the grid. The complete cycle is shown in figure 12.

The result is an environmental friendly power plant and satisfied greenhouse owners who receive heating, electricity, and CO_2 from a single, reliable source, eliminating the need to operate and maintain their own installations.

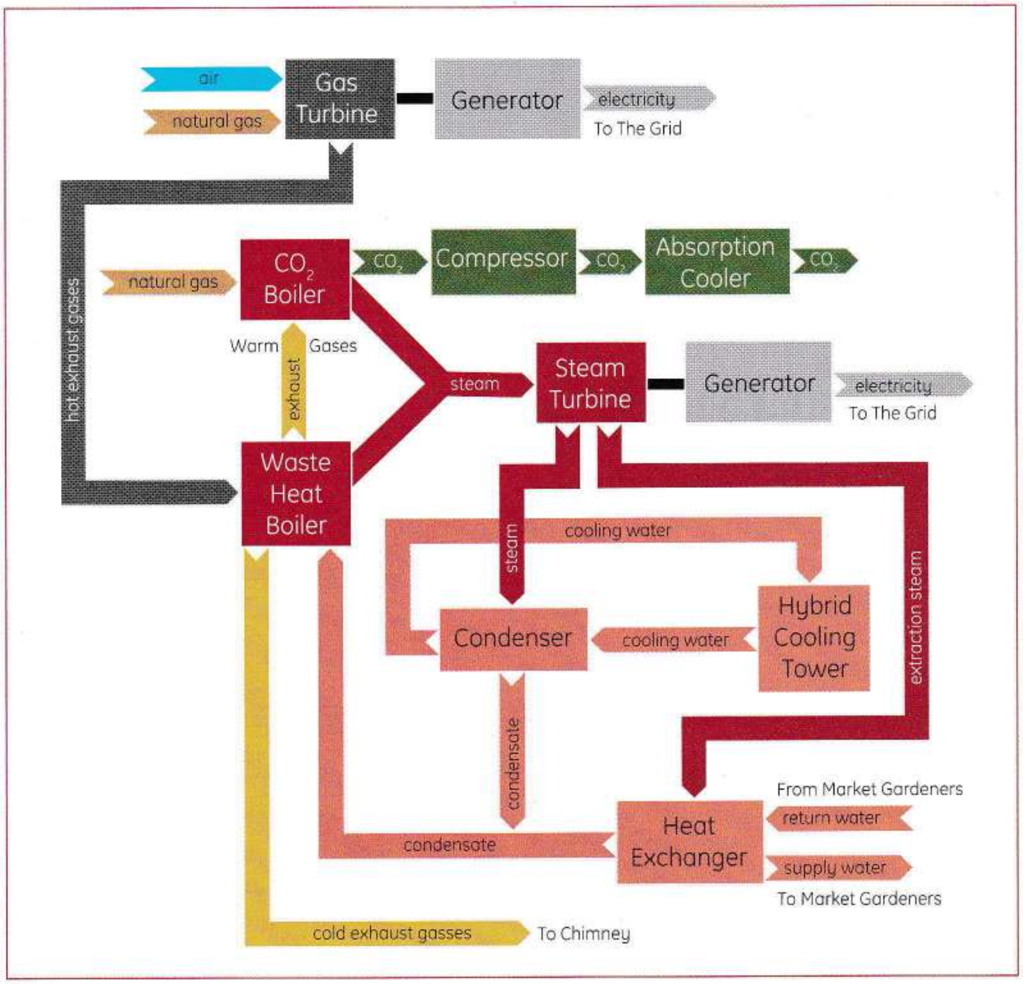


Figure 11 – **Flow diagram of E.ON's ROCA plant.**

The CO_2 compressor showed a sharp resonance around 1500 RPM. With every runup and rundown these resonances caused peaks in the compressor bearing vibration readings, exceeding 150 um p/p. Because the compressor is started and stopped daily, we felt it was important to know the cause in order to judge whether or not such large vibration amplitudes might be damaging to the compressor.

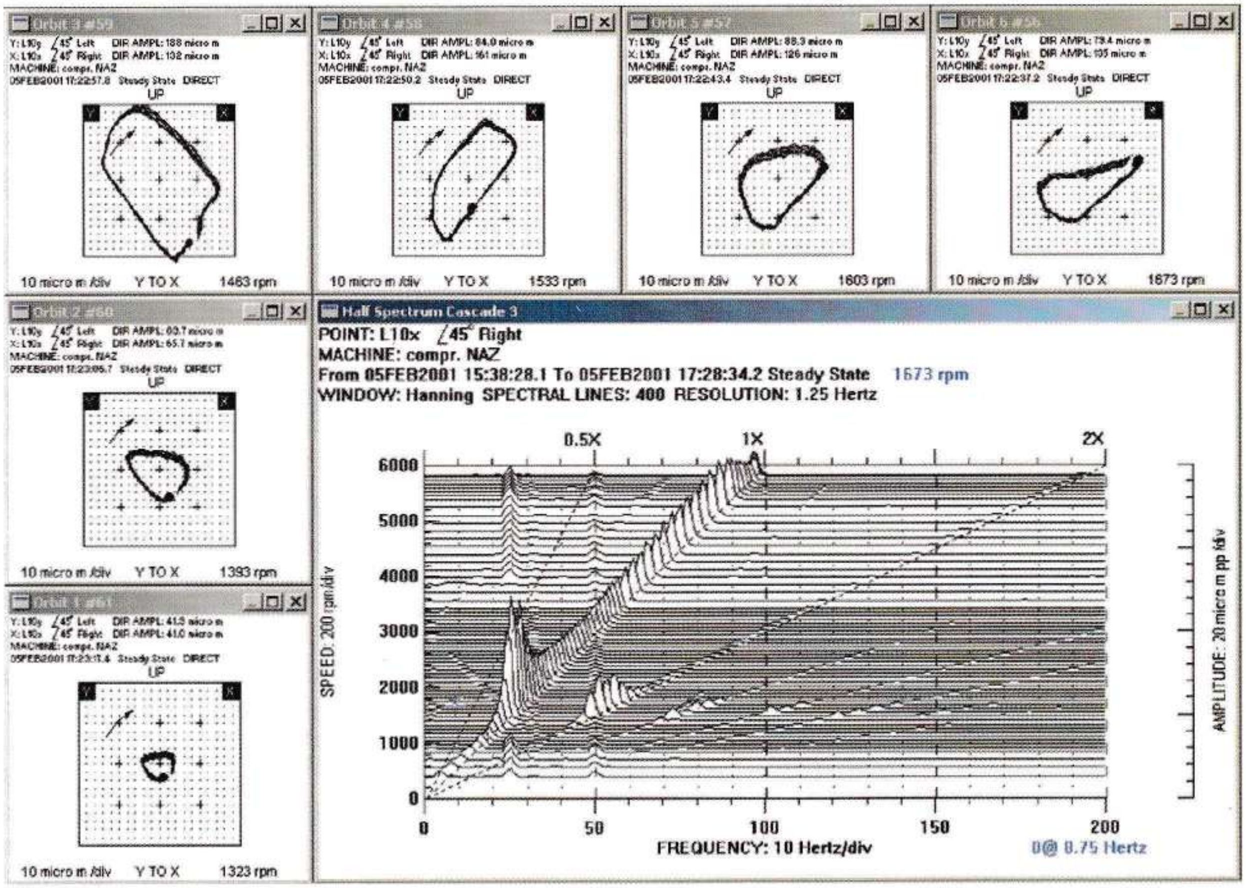
Examination of the spectra collected showed an asynchronous component at 25 Hz, corresponding to a jack up oil pump. To rule out this pump as a possible cause of the resonance, a rundown was conducted and the pump was stopped while the compressor decelerated from 4000 rpm to 1000 rpm. This had no effect on the resonance as shown in figure 12.

During an Advanced Machinery Dynamics course presented by GE Energy in Rotterdam, a Bently Nevada™ rotor dynamic modelling program was used to develop a computer simulation of the rotor. A small unbalance was introduced to the rotor model and it showed a very sharp resonance at 1500 rpm, which exactly coincided with the actual measured resonant frequency. The model was used to calculate any possible internal rubs by the rotor as it passed through resonance, and neither the model nor actual measurements (figure 12) suggested that rubs were occurring.

A quick inspection of the bearings during a stop of the compressor showed no damage, and the behaviour of the bearings was stable. We thus concluded that unbalance was the source of the high vibration and that because it was not resulting in any damage to the machine, a rebalancing could wait until the next scheduled overhaul. We continued to monitor the machine closely via vibration amplitude trends, orbit plots, shaft centreline plots, and bearing temperature trends. This allowed us to save an additional, costly machine outage while permitting us to closely monitor the machine's condition in the interim.

"THIS ALLOWED US

TO SAVE AN ADDITIONAL, COSTLY MACHINE OUTAGE WHILE PERMITTING US TO CLOSELY MONITOR THE MACHINE'S CONDITION IN THE INTERIM."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Orbit 4 #58
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X: L10x ∠45° Right DIR AMPL: 161 micro m
MACHINE: compr. NAZ
05FEB2001 17:22:50.2 Steady State DIRECT
10 micro m /div Y TO X 1533 rpm

Orbit 5 #57
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X: L10x ∠45° Right DIR AMPL: 126 micro m
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Orbit 6 #56
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Orbit 2 #60
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Orbit 1 #61
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10 micro m /div Y TO X 1323 rpm

Half Spectrum Cascade 3
POINT: L10x ∠45° Right
MACHINE: compr. NAZ
From 05FEB2001 15:38:28.1 To 05FEB2001 17:28:34.2 Steady State 1673 rpm
WINDOW: Hanning SPECTRAL LINES: 400 RESOLUTION: 1.25 Hertz

Figure 12 – **Spectrum and orbit plots from CO_2 compressor rundown showing a resonance at approximately 1500 rpm. The orbits show no evidence of a rub. Note also the asynchronous component of the spectrum at approximately 25 Hz, corresponding to the rotational speed of the oil jacking pump. This component is not present between 4000 rpm and 1000 rpm while the pump was intentionally stopped to see whether it had any effect on the compressor resonance.**

Case History 5 Stall damage on a gas turbine

One of our plants uses a gas turbine for the production of steam and electricity. At 3:44 AM on December 17, 2001, a small change in bearing vibration was noticed by the operator. However, because the bearing vibrations are presented to our operators as the highest value from all bearings, the operator had little additional information available to him for assessing the reason for the change. A little over seven hours later, at 11:06 AM, a new increase in amplitude occurred. This increase exceeded the alert alarm value, prompting the operator to ask for assistance from the E.ON diagnostic engineers.

We remotely connected to the plant's Bently Nevada online vibration analysis system and analyzed the data from our office. The shaft vibrations were clearly changed in two distinct steps, as shown in figure 13 for bearings 1 and 2 respectively.

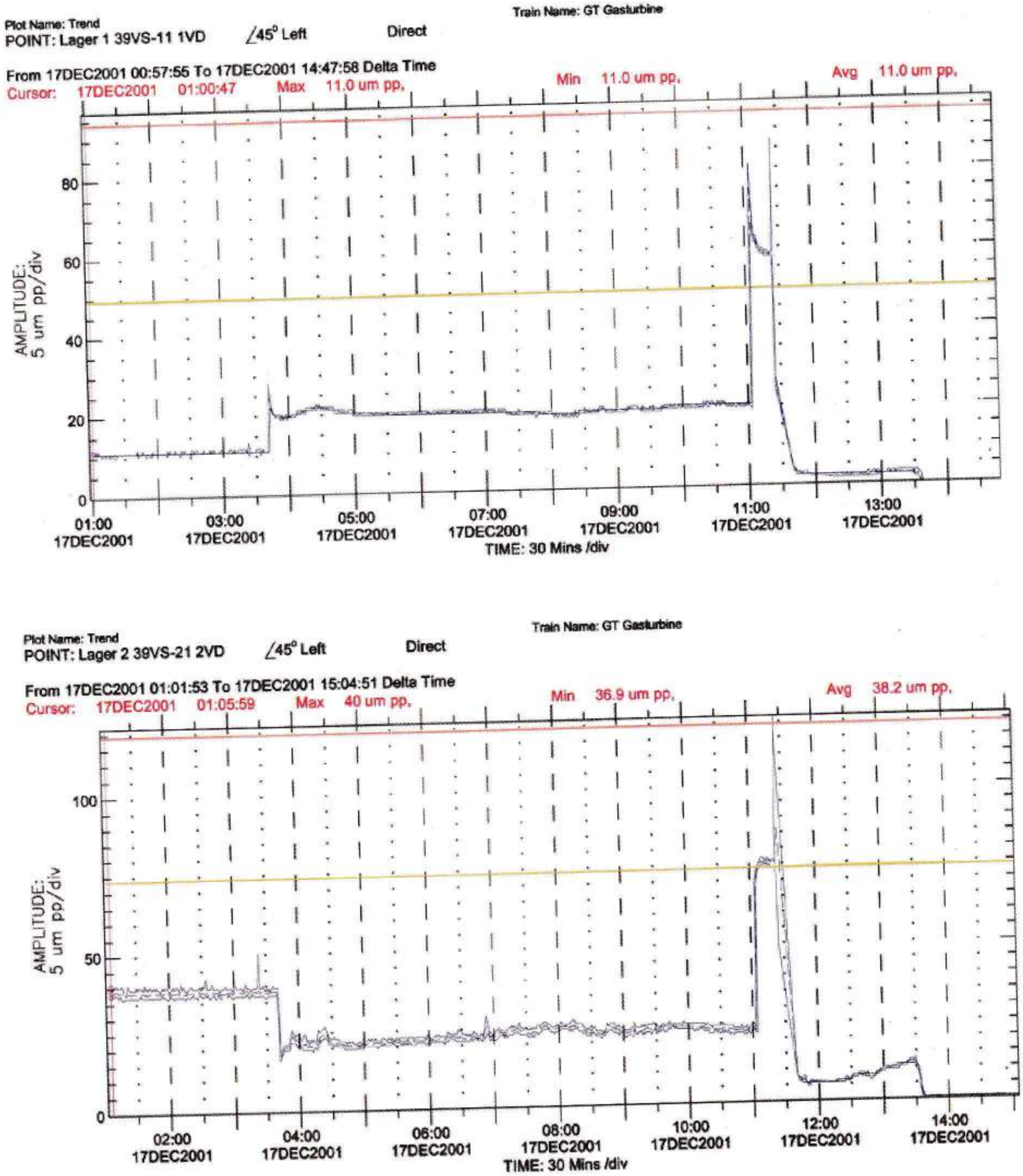


Figure 13 – Trend plot from #1 bearing (top) and #2 bearing (bottom) showing distinct step changes in vibration at 3:44 AM and 11:06 AM on December 17th.

At 3:44 AM, the vibration amplitude increased at bearings 1 and 3, but decreased at bearing 2. At 11:06 AM, the amplitude at all bearings increased. An examination of amplitude/phase vectors from all bearings showed step changes indicative of a serious problem. Combined with other analysis data, we concluded that at least three blade failures had occurred in the compressor section of the turbine, creating instantaneous changes in the balance condition.

Within five minutes from the assistance call, the urgent advice to run down and stop the gas turbine was issued and carried out.

As shown in figure 14, each vector change was surmised to be the result of a blade failure. Vector change A-B occurred at 3:44 AM, while vector changes B-C and C-D occurred almost simultaneously at around 11:06 AM.

After opening the turbine, we found exactly what was expected: broken blades (figure 15). The root cause was diagnosed as compressor stall. The solution was found in the use of counter bore plugs, to prevent flow separating on the inner barrel, together with several other measures to prevent stall in the future.

Although the blade failure occurred without warning, the ability to rapidly and accurately diagnose the problem using our condition monitoring systems undoubtedly helped us prevent further and more costly damage to the gas turbine.

As a result of this experience, we began providing our control room operators with enhanced vibration data using acceptance region plots (figure 16), rather than simply the highest amplitude from each bearing. This data format shows the vectors from all bearings together with visualization of the alarm regions. This has proven to be a quick and reliable way to recognize serious problems.

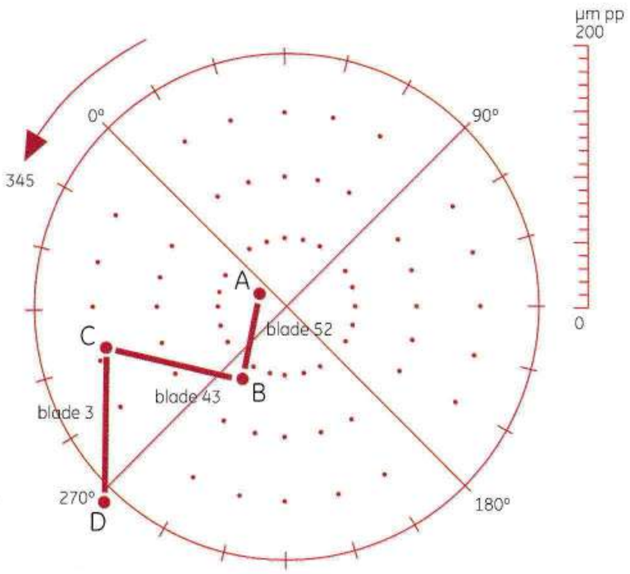


Figure 14 – **APHT plot of bearing #3 vertical probe showing step changes in amplitude/phase vectors Change A-B corresponds to the loss of one blade while vector changes B-C and C-D correspond to the loss of two additional blades.**

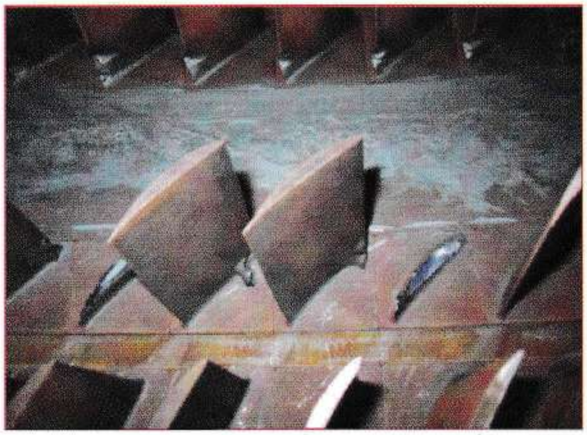
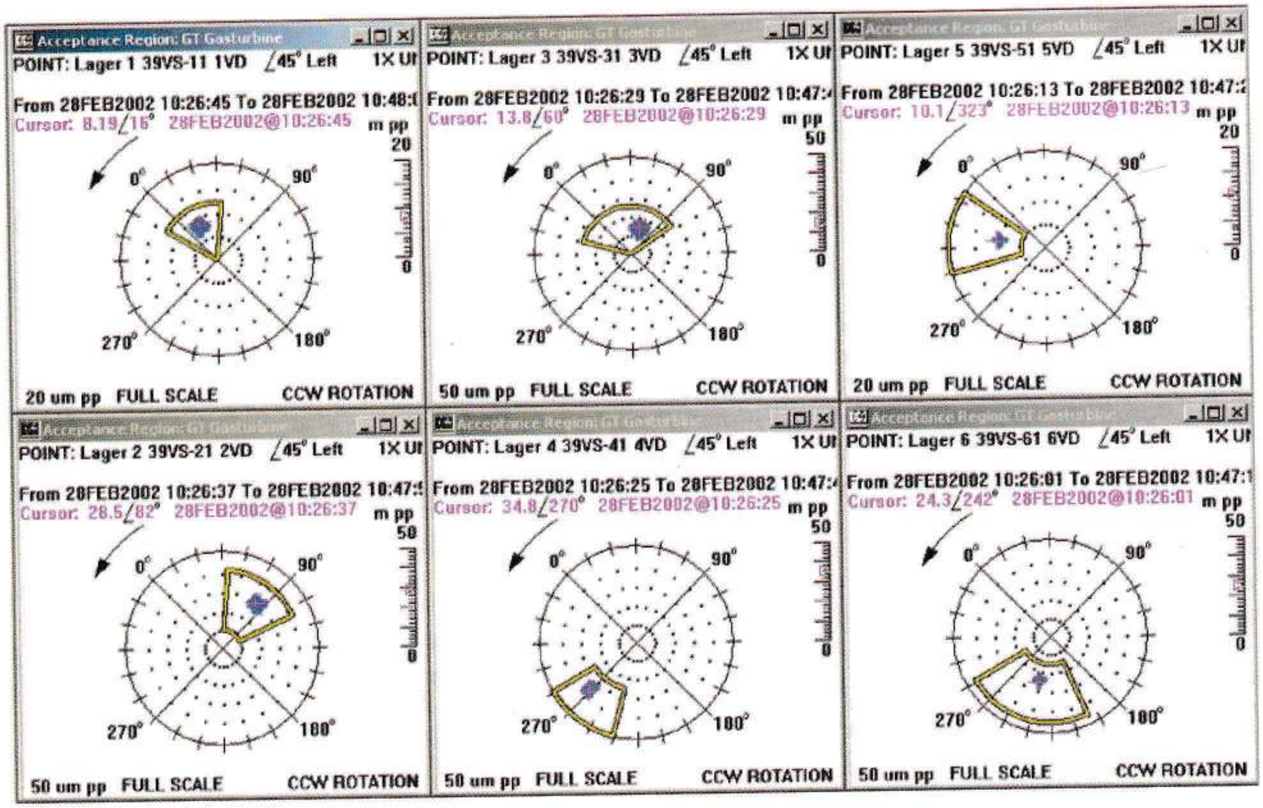


Figure 15 – **Photo showing broken blades on section of gas turbine compressor. The root cause was ultimately traced to compressor stall.**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20 um pp FULL SCALE CCW ROTATION
Acceptance Region: GT Gasturbine
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Acceptance Region: GT Gasturbine
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Figure 16 – **Acceptance region plots are a highly intuitive way of showing allowable amplitude and phase relative to alarm levels. Changes outside of a defined region during steady-state operation are usually indicative of a serious problem.**

Conclusion

With the deregulation of the energy market in Europe during the last several years, the availability of our machines has become much more important. The volatility in energy prices creates an environment in which an unforeseen breakdown can easily cost several million USD. Condition monitoring is a vital part of our strategy because it allows us to predict and plan the maintenance needs for our machinery, thereby decreasing unforeseen breakdowns.

During the nearly 25 years since we began using condition monitoring, we have compiled a very impressive track record across our facilities as shown in Table 3.

During this time, we have also developed and relied upon a systematic method for determining where to apply FDM, UDM, and CDM techniques, allowing us to find an optimal mix of techniques in our overall approach to maintenance, based on an objective analysis of failure modes and effects. Further, rather than assuming that a particular approach remains valid for the life of the asset, we continually reassess our approaches in the light of changing policies, operating conditions, and technologies. For example, as was shown in case history #3, advances in generator inspection technologies introduced in the mid-1990s allowed us to switch from usage-dependent maintenance to condition-dependent maintenance on these assets, enabling a departure from previous maintenance intervals and durations.

Table 3 – Average Statistics Across E.ON Benelux Fleet

Fleet unavailability	3.5% decrease
Time between outages	80% increase
Outage durations	60% decrease
Machine saves and reductions in damage	Numerous

Another important skill gained during this time was the ability to manage risk to the satisfaction of the entities that insure our plants and equipment, giving us the latitude to employ CDM approaches broadly across our facilities, and enjoy the corresponding benefits.

Combined, these results have convinced us, and our management, that condition-based approaches to maintenance are both technically and economically sound. They can be applied by any organization willing to invest in the necessary training and technology, and willing to change the way they work.

Editor's Note: *Much of the material in this article was first presented by the author in the paper "Fifteen Years of Experience with Condition Monitoring for Steam Turbine and Generator Systems" at the ARAB Electricity Conference in March 1997* [1]. *At our request, it has been updated for publication in ORBIT and augmented with additional case histories.*

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Reliability? Yes We Can.

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"THE APPROACH WE HAVE TAKEN IS TO 'BOTTLE THE RECIPE' OF TOP RELIABILITY PERFORMERS AND DISTILL IT INTO A METHODOLOGY THAT CAN BE APPLIED ACROSS MULTIPLE INDUSTRIES TO IMPROVE RELIABILITY—EVERY FACET OF IT."

In the cover story for this issue of ORBIT, MRG's Bob DiStefano and GE's Larry Covino, make a compelling case for reliability improvements and helping customers create the "business case" for reliability improvement in their organizations. But making the business case is merely the first step—then, you have to act on it. I'm pleased to announce that GE Energy now provides a comprehensive reliability offering encompassing the best methods and tools available today, coupled with the ability to implement anywhere in the world.

The approach we have taken is to "bottle the recipe" of top reliability performers and distill it into a methodology that can be applied across multiple industries to improve reliability—every facet of it. We teamed with the very best company we could find to help us—one that had nearly 20 years experience in performing reliability-related engineering projects and in establishing successful reliability programs for their customers. That company is Management Resources Group (MRG), Inc. and they boast fully 50% of the Fortune 500 among their client list. They've been responsible for some dramatic "reliability transformations" in our industry segments, with results that go far beyond just maintenance metrics and reach all the way to bottom line business results.

I'm extremely excited that we've recently formalized a long-term Strategic Business Relationship with MRG that provides GE with the training, tools, and methodologies used by MRG in hundreds of successful projects over the last two decades. With GE's global network of highly skilled engineers, we now have the ability to help customers on every continent with every aspect of their reliability efforts—from CMMS implementation and usage to spare parts inventory strategies, RCM training and maintenance strategy implementation to risk assessment and mitigation, and much more. Whether a customer needs help with just a single facet of their reliability efforts, or needs assistance with their entire program, we now have the people and the know-how to make a difference.

Our GE offering is specifically designed to be different from traditional reliability "consulting" because we believe that most reliability offerings today lack a key ingredient—implementation support. When a consultant merely makes recommendations, but isn't part of the team that has to implement those recommendations, the results can often be underwhelming. Many companies have the will to improve, and even a sound plan, but they often lack the resources to deploy to a project as substantial as a company-wide or even plant-wide reliability program. Likewise, many companies lack the ability to produce results consistently across the multiple locations that make up their enterprise. GE can help here by providing the services needed to complete the detailed engineering and implementation involved in creating equipment hierarchies, conducting FMEA studies, populating reliability databases, and all the other details. And, we do this against a defined set of standards that will ensure that the right results can be consistently achieved.

As our sales and service teams around the world interact every day with customers related to instrumentation, condition monitoring, plant optimization, and controls-related topics, the bigger picture continues to emerge: the need for additional technologies, services, and an overall program approach that helps our customers take their reliability efforts to the "next level". Condition monitoring (CM) is one major component in any well-rounded reliability program, but our experience has shown that without a top-tier reliability program in-place, CM systems often cannot provide their maximum operating benefits. By augmenting our business capabilities in a way that better addresses the overall reliability challenge rather than just parts of it, we are better able to help you achieve your reliability goals than ever before. I encourage you to contact us and explore what we can do to accelerate and improve your reliability endeavors.

"OUR GE OFFERING IS SPECIFICALLY DESIGNED TO BE DIFFERENT FROM TRADITIONAL RELIABILITY 'CONSULTING' BECAUSE WE BELIEVE THAT MOST RELIABILITY OFFERINGS TODAY LACK A KEY INGREDIENT—IMPLEMENTATION SUPPORT."

Enterprise Reliability: Changing the Game

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Changing the Game

Admittedly, "changing the game" is a pretty bold statement. Can a company really transform its business results through transforming its approach to reliability? The answer to that can be found in the dozens of successful case studies we've compiled in the last several years, two of which we provide here.

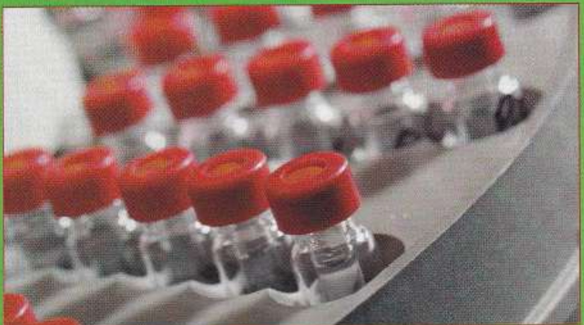
✦ Case Study 1 ✦

A large steel mill was on the verge of bankruptcy. They turned to reliability as a strategy to turn things around and worked with an outside party to implement an integrated, plant-wide reliability centered maintenance program. As a result, the plant became the most profitable steel producer in North America and was rated the #1 steel mill in the world by Dow Jones. This plant reduced reactive maintenance from 70% to 20%, increased availability from 78% to 91%, improved First Run Yield from 76% to 91%, and decreased storeroom inventory by $40 million—all with fewer people.

✦ Case Study 2 ✦

A drug patent from a major pharmaceutical supplier was about to expire, giving way to substantial competition from those providing a generically equivalent drug. Faced with these challenges, the plant responsible for manufacturing this drug would need to completely revamp its operations or be driven out of business through low-cost competition. Closure of the plant would affect thousands of employees. By instituting a holistic and aggressive reliability program and by working with a reliability partner to assist them, the plant was able to not just keep its doors open, but to maintain a leadership position for this particular drug, even in the face of stiff, low-cost competition.

These companies were serious about "changing the game" and their results attest to that. In the remainder of this article, we'll answer some fundamental questions about reliability—what it is, what it can do for you, and the business case for initiating or revitalizing your reliability program.



"IN THIS ARTICLE, WE'LL ANSWER SOME FUNDAMENTAL QUESTIONS ABOUT RELIABILITY—WHAT IT IS, WHAT IT CAN DO FOR YOU, AND THE BUSINESS CASE FOR INITIATING OR REVITALIZING YOUR RELIABILITY PROGRAM."

What is Reliability?

Optimization of plant asset performance and reliability is essential to meeting the challenge of increased production and lower costs—a situation faced by many industries in increasingly competitive global markets. Successful plant asset optimization requires the strategic integration of proven technologies, maintenance best practices, and reliability methodologies in a coordinated, sustainable program that includes culture change. Reliability is the over-arching term that defines this program.

By definition, reliability is: "The probability that a system, device or component will perform its prescribed duty without failure for a given time when operating correctly in a specified environment."

We term reliability as the strategy and resulting programs that need to be in place to make sure that the systems, devices, and components will indeed perform their prescribed duty without failure. When we talk about reliability, we are talking about the strategy, methodologies, and programs that will drive the actions required to achieve the optimization of your plant assets. A holistic approach to reliability brings all of these programs and initiatives together into a comprehensive, ground-up approach built around solid foundational elements. Without a solid foundation, many strategies and programs falter and ultimately fail to achieve their objectives.

Reliability is more then condition monitoring and predictive technologies. Although they are integral components of most successful reliability programs, reliability, as defined above, encompasses much more as part of successful plant asset optimization. Reliability-focused strategies and program development will drive the use of the right mix of technologies (including condition monitoring and predictive tools) based upon the asset failure modes, impact of failure, and consequences of failure on customer-specific key business drivers.

Why is Reliability Important?

Comparison of actual operating results show that "Best in Class" reliability performers typically spend about 60% less on maintenance than industry averages while simultaneously achieving better results in every meaningful category —process uptime, labor efficiency, equipment availability, safety, environmental compliance, and of course profitability.

Not surprisingly, many companies are now realizing that reliability is the "next frontier" for enhancing business results. Investment in enhanced reliability programs often yield mutli-year ROIs of 8:1 and can run as high as 50:1 in some instances. In short, many businesses are beginning to embrace reliability as a "game changer" in meeting increasing competitive pressures and in satisfying customer and shareholder demands.

How is Reliability Measured?

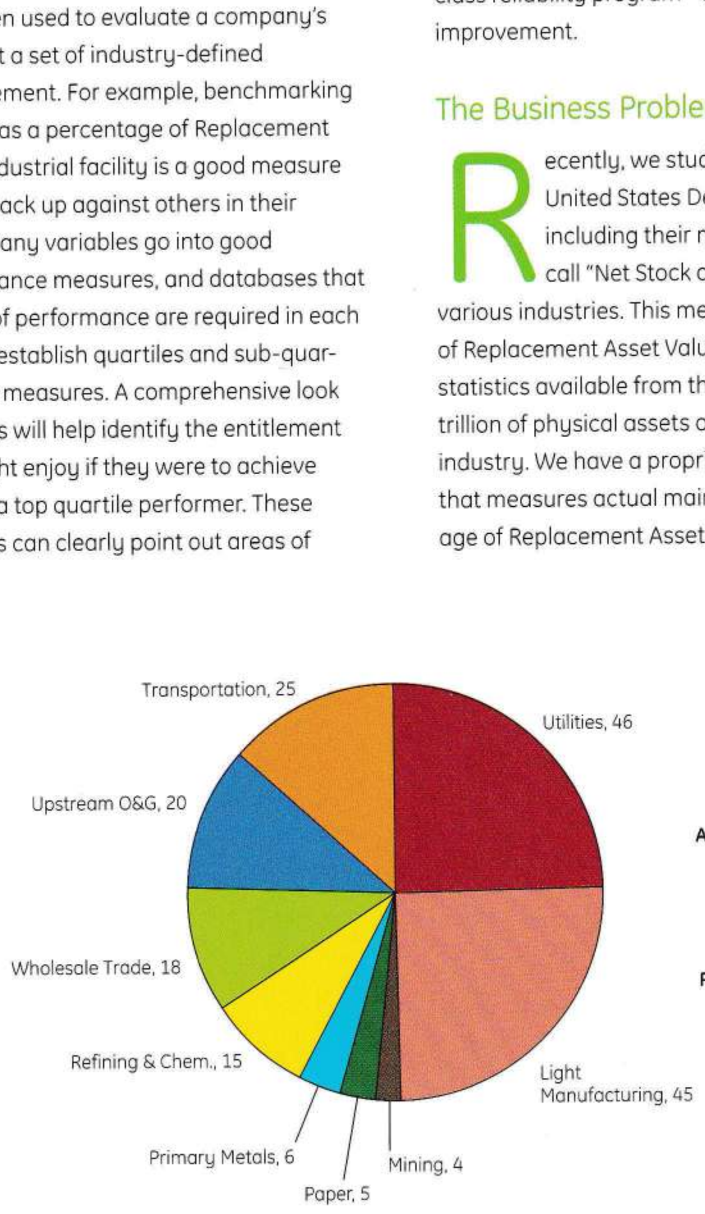
Every company has key business drivers that they actively measure and manage that can be directly influenced by improvements in their program around maintenance and reliability. These business drivers typically include environmental and regulatory compliance, employee and public safety, operational drivers such as availability and production, quality (such as first pass quality and yield), and of course operation and maintenance costs. Improvements in any of these areas can directly influence the bottom line financial statement for most industrial customers. A comprehensive, holistic approach to reliability focuses on developing a program that will raise the level of performance in all of these applicable business areas. Like most metrics, there are other parameters that are important to measure to assure that improvements are being made. These are typically called key Performance Indicators (KPIs), and are developed and implemented as part of the reliability program development, enabling progress to be tracked.

Working with all the key stakeholders in developing these KPI's is integral to gaining awareness and ultimately buy-in to achieving and exceeding the defined measures.

Benchmarks are often used to evaluate a company's performance against a set of industry-defined standards of achievement. For example, benchmarking maintenance spend as a percentage of Replacement Asset Value for an industrial facility is a good measure of how they might stack up against others in their industry segment. Many variables go into good benchmark performance measures, and databases that span various levels of performance are required in each segment in order to establish quartiles and sub-quartiles of performance measures. A comprehensive look at these benchmarks will help identify the entitlement an organization might enjoy if they were to achieve the performance of a top quartile performer. These benchmark statistics can clearly point out areas of focus where even well-established and comprehensive programs can achieve additional benefits. To date we have not found any organization that is 100% satisfied that they have achieved all of the benefits of a world-class reliability program—there is always room for improvement.

The Business Problem

Recently, we studied statistics from the United States Department of Commerce, including their measurement of what they call "Net Stock of Private Fixed Assets" in various industries. This measurement is a close proxy of Replacement Asset Value (RAV). In 2003 (the latest statistics available from the USDOC), there were $4.9 trillion of physical assets on the ground in United States industry. We have a proprietary benchmarking system that measures actual maintenance spend (as a percentage of Replacement Asset Value (RAV)) in about 10



$184 Billion
Annual Excess Maintenance Spend
+
$553 Billion
Productivity Losses
=
$738 Billion
Potenial Anuual Reliability Benefit

Figure 1 – **Annual Excess Maintenance Spend (in billion USD) by US Industry.**

Table 1 – Unintended Consequences of Maintenance Spend Reductions without a Robust Reliability Program

Increased downtime
Degraded equipment reliability/condition due to failure to perform preventive maintenance
Diminished product quality
Less-than-optimal asset utilization
Missed product deliveries
Reduced productivity
Downtime from stock-outs (not having the right spare parts when needed)
Increased energy consumption
Avoidable collateral damage due to catastrophic failures

different industries. As it turns out, the average spend is between 5% and 8%, with the best performers spending less than 2% to 3%. Again, this is actual performance data—not theoretical data—and the nearly two decades of reliability services data compiled by MRG through experience with over 400 clients in 14 industries bears this out consistently.

We applied our proprietary benchmarking system to the U.S. Department of Commerce statistics, and we dollarized the value of elevating Fourth, Third, and Second Quartile plants to First Quartile in maintenance spend. The results are shown in Figure 1 and suggests that industry wastes more than $180 billion in excess maintenance spend annually. This figure is even more sobering when you consider that it is just for the U.S.

Just Spend Less?

Reducing the maintenance spend alone is not the answer. In fact many companies in the past 15 years have cut maintenance budgets fairly dramatically; however, performance in other aspects of the business has suffered—and in many cases, suffered dramatically. For example, efforts to cut overtime and use of contractors and materials costs have had unintended consequences, as summarized in Table 1.

Simply cutting the maintenance budget without a genuine reliability strategy will thus result in other costs that eclipse any savings in spending. The work done in the 1980's and 1990"s by Rohm and Haas (a recognized leader in this area), as well as numerous published case studies, show consistently that the opportunities associated with these other performance deficiencies can represent 3X to 7X the maintenance spend reduction benefit. Taking the conservative end of that statistic (three times maintenance spend reductions), you can see from Figure 1 that another $550 billion in "Productivity Losses" can be re-claimed through the maintenance and reliability improvements, making the financial business case—again, in the United States alone—worth close to $740 billion in annual, recurring benefits.

What is this number world-wide? Good question. We are currently trying to quantify that with good data; however, our preliminary reading is that, if the U.S. opportunity is conservatively estimated at $740 billion annually, the world-wide annual benefits are probably between $2 and $3 trillion.

Reliability Adoption Curve

With approximately 25% of plants having achieved "best-in-class" reliability performance (i.e., top quartile performance), this translates to a market as a whole that is in the Early Adopter/Early Majority stage. In other words, 75% of plants have improvements to make and work to do. Figure 2 depicts this via something called the "Reliability Adoption Life Cycle Curve."

While such curves are often used to quantify where the market may be with regard to the latest technology (such as how many homes have broadband internet access versus dial-up), Figure 2 represents much more than just adoption. In the case of reliability, it also represents a glimpse into the competitive landscape. Early adopters are not playing "catch up" or "me too" to try and achieve performance equal to competitors. They are essentially pulling ahead of their competitors and enjoy the benefits of improved reliability until their competitors eventually are forced to respond in similar fashion. Those who adopt earlier accrue benefits for a longer period of time and with greater differentiation than those who wait until "late in the game" to make such adjustments.

This is the situation when we look at plant-by-plant adoption. In contrast, when we look for an example of a company that has uniformly elevated their reliability practices enterprise-wide, rather than just plant-by-plant, we find a different situation: there are no examples. In other words, we are still looking for the innovators. This is not because there is no perceived need or because there is no corresponding business

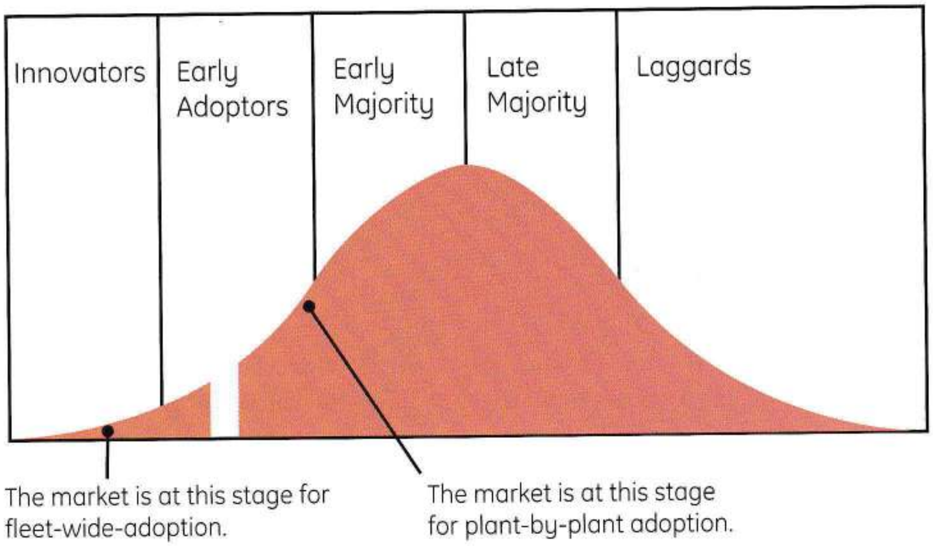

Innovators
Early Adoptors
Early Majority
Late Majority
Laggards
The market is at this stage for fleet-wide-adoption.
The market is at this stage for plant-by-plant adoption.

Figure 2 – **Reliability Adoption Life Cycle Curve.**

case for enterprise-wide improvement versus simple plant-by-plant improvement. The issue is one of implementation. While there are numerous companies that have been able to achieve "best in class" at isolated plants, they simply haven't been able to unlock the "recipe" for replicating this success uniformly and consistently across all of their plants. Nobody has done it because, without assistance, nobody has been able to.

What are the benefits of enterprise-wide approach rather than plant-by-plant? There are several:

- It leverages work done at one plant for reuse at other plants, eliminating the need for each and every plant in an enterprise to re-invent the wheel.
- This results in a lower overall investment across an enterprise, making it easier to justify the expenditures for foundational and culture change work, enhance the Return on Investment, and speed the Rate of Return.

Typical ROIs are from 8:1 to 16:1 and higher, with typical Internal Rates of Return of from 50% to 250% and higher.

The Business Case

As recently as five years ago, it is fair to say there was very little awareness at the corporate executive suite level regarding the contribution to financial and business performance improvements that can come from improved levels of physical asset reliability. In addition, five years ago we did not enjoy an accepted consensus among industry experts about what good maintenance and reliability practices look like. If we asked what are the characteristics exhibited by top performers who have increased operational performance of their physical assets—while reducing the overall cost of production (including reducing the cost of maintenance), we were likely to get varying answers depending on who was asked. In fact, as recently as five years ago, there were no true success stories in this arena. There were some spotty, incremental achievements, but no reliable success stories. Gladly, today we have much higher awareness at executive management levels, and we have consistent guidance from top performers and consensus among industry experts about the proven pattern of excellence.

First lets discuss executive awareness. Today, the people in the executive suites of our industrial companies are beginning to understand that the business problem described earlier is solvable, and the solution represents the largest company performance improvement opportunity available. This is partly because corporate executives have read about or witnessed dramatic business performance improvements in the early adopter companies. The CEO of Chevron Corporation, Mr. Dave O'Reilly, said in a recent letter to employees that "Reliability, like safety, is a critical element of operational excellence and requires our constant attention." The Vice President of Operations at Anheuser Busch, Michael Harding, said in a recent public speech to the Society of Maintenance and Reliability Professionals, that "As goes maintenance, so goes the business". There are more and more examples of executives focusing on maintenance and reliability every day.

Is there a financial business case for reliability in your plant or enterprise? Find out what initiative your CEO is concerned with, and we guarantee you that reliable assets will materially contribute to the results of that initiative—either directly or indirectly.

This will be further explored later in this article. For now, suffice to say that this environment of increased awareness and understanding bodes well for a significant elevation of maintenance and reliability business practices. There is a lot of guidance that can be used to estimate the costs of closing gaps to achieve higher levels of performance and the associated financial gains. While such costs are not insignificant, they are almost always easily justifiable in light of the benefits.

Today, although there are only a handful of companies that have, in fact, seriously elevated their maintenance and reliability practices, and improved business performance as a result, those few companies provide ample data that paints a very consistent picture of what good looks like and what results can be expected. Companies like Rohm and Haas (mentioned earlier), Allied Signal/Honeywell, Dofasco Steel, and, more recently, Cargill Corporation, among a few others, have made dramatic shifts in their physical asset management strategies that have driven significant financial results in many parts of their businesses.

Best-in-Class Traits

The characteristics exhibited by these "Early Adopters" are remarkably consistent regardless of the industry in which they operate. These characteristics allow at least six key lessons to be drawn that are widely applicable to any industry.

1. They spend less on maintenance without sacrificing business results.

Annual maintenance spends of these companies are typically less than 2-3% of Replacement Asset Value (RAV). Contrast this with an industry average maintenance spend of 5-8% RAV. In other words, best performers are spending about half of what industry average performers are spending.

2. They employ a variety of Predictive Maintenance (PdM) and Condition Monitoring (CM) technologies on the majority of the candidate equipment population.

Of note in the top performers is the depth into the asset population to which these multiple PdM and CM technologies are applied. For example,

- From 63% to 95% of rotating machines (depending on the industry) are included in a robust vibration analysis program—not just the critical equipment.
- 91% to 100% of electrical equipment is included in a robust thermography program (incidentally, 58% to 79% of mechanical equipment is also included in the thermography program at top performers, particularly smaller motors and gearboxes in packaging and similar operations).
- Lubrication analysis and contamination control practices are extensive and comprehensive.
- Use of Motor Circuit/Current Evaluation (MCE) technology for drivers is extensive.
- Extensive use of ultrasonics (airborne and contact) and various non-destructive testing (NDT) technologies for piping and pressurized assets is also present at top performers.

3. They employ time-based, invasive preventive maintenance (PM) on a relatively small percentage (usually only about 25%) of their equipment.

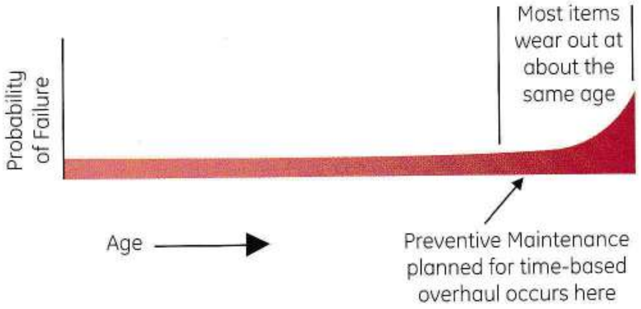


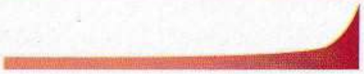
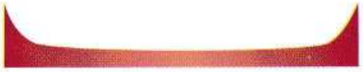
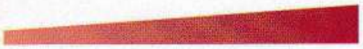
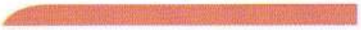
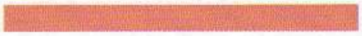
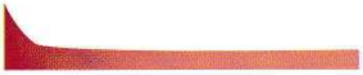
Figure 3 – **Traditional View of Asset Wear.**

These last two points are worth considerable emphasis. After World War II, it was believed in general industry (despite knowledge to the contrary in the aerospace industries and some branches of the United States military) that most equipment behaved in a time-based predictable pattern. That is, the probability of failure was relatively low and constant until a so-called "wear-out" zone was reached, at which time exponential increase in failure probability occurred. Traditional time-based Preventive Maintenance was designed to intervene into the equipment right before the wear-out zone was reached. Figure 3 illustrates this and is taken from the book RCM-II by John Moubray.

In reality, a precious small percentage (only about 2%) of equipment actually behaves in this fashion.

In fact, as shown in Table 2 (again taken from RCM-II by John Moubray), there are many failure patterns of machinery behavior, but only about 11% of the equipment in a typical industrial plant exhibits a **time-based** predictable "wear-out" pattern.

Table 2 – Modern View of Asset Wear

Description	Graphical Representation	% of Assets		Examples
A. Traditional View Random failure, then wear out zone		2%	11% (primarily time-based wear)	Sprockets and chains
B. Bathtub Curve High infant mortality, then a low level of random failure, then a wear out zone		4%		Typically electro-mechanical items. Electronic components give rise to infant mortality on left side of curve, while mechanical components give rise to late-life failure.
C. Slow Aging Steady increase in the probability of failure		5%		Brake pad linings or other friction-type mechanisms
D. Best New Sharp increase in the probability of failure, then random failure		7%	89% (primarily random wear)	Hydraulic and compressed air systems
E. Constant Random Failure Truly random with no age-related failure pattern		14%		Rolling element bearings
F. Worst New High infant mortality and then random failure		68%		Electronic instruments

In Table 2, note the phenomenon of infant mortality, depicted in curves B and F by the initial high probability of failure upon commissioning an asset into service. This corresponds to about 72% of equipment in a typical industrial plant (this of course varies by industry) that experiences infant mortality, while, again, only about 11% has a time-based predictable wear-out pattern. Thus, by relying predominantly on calendar-based PM as a maintenance strategy for most of our assets, we are potentially adding value on only a small percentage of equipment, and potentially introducing infant mortality on a high percentage of our assets—unnecessarily—doing more harm than good. Have you ever been confronted by a school of thought that held "if it ain't broke, don't fix it?" While you may have thought anyone espousing this philosophy was unaware of the science of machinery behavior, it turns out that they really are expressing a knowledge based on their own experience that machine failure is very likely shortly after doing work on a machine. They may not have known the engineering principles behind the experience, but they were right!

We are not suggesting that because most equipment does not observe a time-based predictable failure pattern we shouldn't do anything to our machines until they fail. We are saying that despite the fact that most of our machines do not observe a time-based predictable wear-out pattern, failure is predictable on a large percentage of our equipment - using predictive maintenance and condition monitoring. Eliminating the unnecessary calendar-based PMs and introducing PdM enhances our ability to proactively manage our assets to be more reliable, and reduces the cost of maintenance at the same time.

4. They allow their PdM technologies to be the primary driver of their work identification system.

Here are some statistical highlights of top-quartile workflow practices:

- Over 50% of the daily work order hours are related to the PdM program
  - 15% Collecting and Analyzing Condition Information
  - 35% Performing PdM "Results" Corrective Work (PdMr)
- About 30% of the daily work order hours are related to the PM program
  - 15% Collecting and Analyzing Condition/ Operating Parameters
  - 15% Performing PM "Results" Corrective Work (PMr)
- Less than 20% of the daily work orders were initiated via a traditional work request from equipment operators

Keep in mind that the use of the PdM technologies objectively identifies corrective work based on real science and real data, and the early and objective identification of machine faults, if acted upon properly, should avoid catastrophic failure and collateral damage. This means that the repairs that are made are typically less extensive, using less labor and less parts. This all drives costs down.

Traditional work identification based largely on the "five-senses" of the equipment operators provides inadequate time to effectively plan corrective work, which handicaps schedule compliance, in turn undermining the credibility of and trust in maintenance on the part of the operators, and so on. The domino

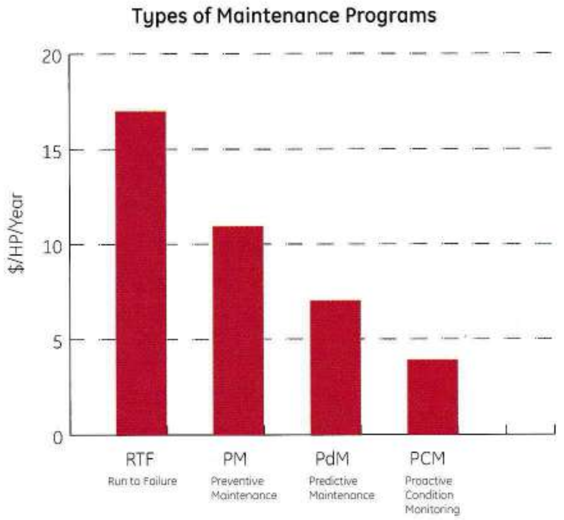


Figure 4 – **Cost of maintenance versus maintenance practices employed, as summarized by an Electric Power Research Institute (EPRI) study.**

effect is clearly present here if the root cause of the problem—work identification—is not addressed. A top-quartile, objective work identification system, based on comprehensive PdM, allows the Planners to plan the PM and PdM corrective work orders. By virtue of early and objective machine fault identification, these work orders can be effectively planned because we have ample time. Once planned, these work orders can be advanced to a ready-to-schedule status—feeding a more effective scheduling process. This, in turn, allows wrench time of the maintenance workers to approach (and in some cases exceed) 50% (note that the average wrench-time in a typical industrial plant is less than 30%). This also eventually will allow the equipment operators to trust the schedule and actually prepare the work-site and the equipment for the scheduled repair.

Of course, there are many studies that prove planned work is significantly less expensive than unplanned work. In addition, a work mix more heavily weighted toward PdM will drive costs down, as Figure 4 summarizing one study shows.

In addition, a well-planned work order provides ample time for an experienced and skilled craftsperson to perform a precision repair that should result in more reliable operation once the machine is restored to service, not to mention more personal job satisfaction on the part of the craftsman who was given ample time to do the job right the first time.

5. They treat reliability holistically.

Top performers all exhibit a holistic approach to changing practices, recognizing that the benefits cannot be unlocked by attacking individual components of the entire strategy. If only the maintenance people are involved in the process, it won't drive results. The entire organization must be involved to unlock the benefits. And, all aspects of the strategy must be addressed simultaneously. You cannot piecemeal your way to prosperity. For example, planning and scheduling cannot improve if the work identification system is faulty. We can't identify work objectively and early (before collateral and catastrophic damage occurs) without extensive use of PdM and condition monitoring. "Results" work orders will never be slotted into the schedule unless the operators understand and trust the technology. This is just a small example of how every aspect of the strategy acts as a link in the chain. If any link is missing, or broken, the entire strength of the chain is compromised.

6. They do not overlook the importance of culture change.

The sixth critical lesson drawn from top performers is that the culture change required to accomplish success is recognized early as a significant impediment to success. These top performers incorporated all kinds of tools and methods to address culture change, including awareness training, consistent measurement systems, alignment of performance to rewards, etc. In fact, the top performers believe that the most challenging part of their journey was the "softer side" of the problem—not the technology and engineering side. If we think in

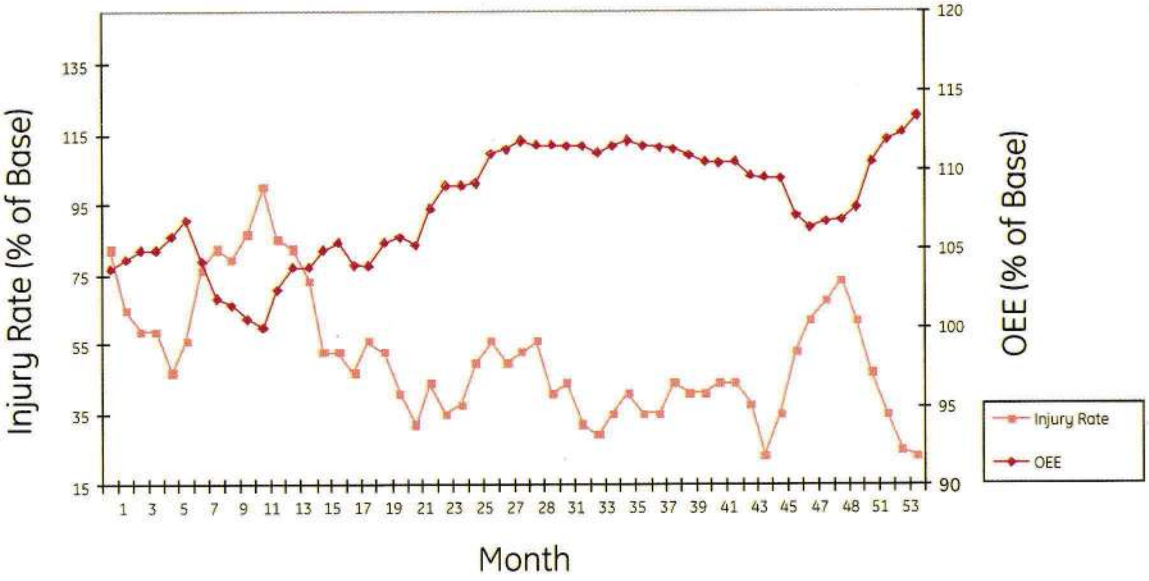


Figure 5 – **Injury Rate and Overall Equipment Effectiveness (OEE).**

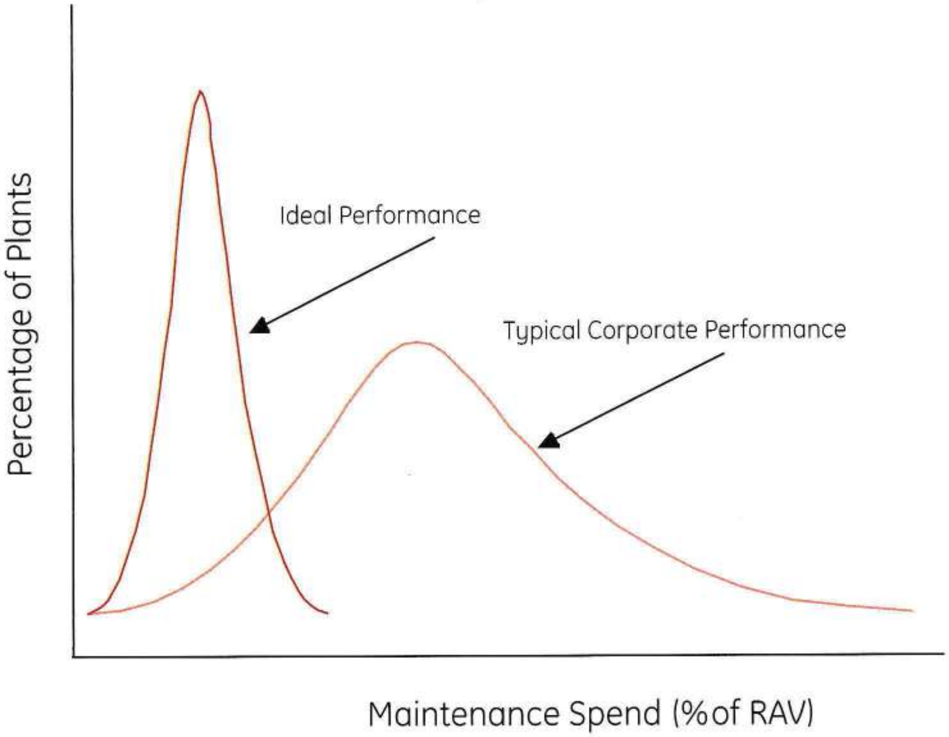


Figure 6 – **Enterprise-wide Reliability Adoption Goals.**

terms of people, process, and technology (which many companies do today), not surprisingly it is the people aspect that is the most challenging. Despite our intuition that this is true, most companies fail to dedicate the proper amount of attention and resources to this aspect. For example, many companies complain that their Computerized Maintenance Management System (CMMS) has not delivered the promised results, but the CMMS alone cannot deliver reliability. Concentrating primarily on the process and technology does not result in sustainable higher performance. Research done on culture change over a twenty-year period inside GE revealed remarkable statistics. 100% of change initiatives that were considered successful had a sound technical solution. However, over 98% of change initiatives that were considered failures also had a sound technical solution! This amplifies the experience that a sound technical solution alone will not drive results.

Why do reliability programs/ initiatives fail?

Despite the success stories that should guide us with their consistent practices, even the successful companies that have achieved great results have done so only in the context of individual plants or business units. None of the case studies for success have demonstrated uniform elevation of these practices enterprise-wide, at every single plant. In addition, the success that is evident is still somewhat (if not highly) dependent on influential leaders without whom the performance is not sustainable. In other words, in some of these companies, the changes have yet to be institutionalized for sustainable performance and continuous improvement. This, of course, takes time, resources, and perseverance, and it should be pointed out that some of the companies recognize this and are actively addressing it.

If we are looking for a parallel to guide us in institutionalized and sustainable change across the entire enterprise, we need look no further than the area of safety. Those of us who are old enough can remember a day when safety was a responsibility of a limited number of people in a department. Today, safety is knitted into the fabric of every industrial company, and it is everyone's responsibility. It is part of the way we do business. Safe working practices are enabling other business performance improvements that would not be possible otherwise. It is worth referring here to Figure 5 showing the remarkably direct correlation that has been established between Injury Rate and Overall Equipment Effectiveness (OEE), presented some time ago by Ron Moore of The RM Group, Inc.

Reliability needs to become knitted into the fabric of our companies much like safety has. Why? Consider that every corporate improvement initiative, whether it is related to Lean Manufacturing, TPM®, Six Sigma®, Quality Circles, Supply Chain Optimization, Market Share Increase, Cost-of-Goods Reduction, Value-added Services, Increase in Sales, Asset Utilization Leverage —no matter what it is—success in these initiatives is either directly or indirectly enabled and enhanced by the reliability, stability, and dependability of the physical assets. There are incremental benefits related to all of these programs that are "locked" without addressing a fundamental foundational aspect of our business—namely rendering our physical assets reliable—and doing so efficiently. Could the injury rates at the companies that show direct correlation have gone down to those levels without reliable assets? Absolutely not. If you consider benefits of implementing Lean Manufacturing Practices, which many of our clients are doing, we have seen or heard of cases where significant lean principals were applied in manufacturing plants only to uncover previously hidden reliability issues. With all of the flexibility and wasted movements removed from the plant, unreliable or unstable assets are unmasked and result in larger production penalties because there is no flexibility to adjust and react. So business performance can actually degrade if "Lean" is implemented in the absence of establishing a reliable and stable asset base. In any event, if this reliability foundation is in place, incremental benefits for the corporation can be unlocked and the performance of the company, in whatever part of the business the executive suite is focused on, will improve.

Nonetheless, some obvious impediments stand in the way of uniform, enterprise-wide performance, including:

- No business case developed to frame the opportunity in financial and business terms
- Lack of executive initiating sponsorship
- Lack of executive sustaining sponsorship
- No defined standards at the corporate or division level
- Failure to recognize the need for careful integration of all the elements in a top-quartile asset management practice
- Insufficient attention to addressing culture change
- Tepid application of PdM and CM as primary work identifiers
- Inordinate reliance on calendar-based PM
- No ties between performance and rewards
- Missing systems/tools to efficiently leverage work done at one plant to similar equipment at other plants
- Failure to employ outside resources for special expertise, leadership, guidance, and actual heavy-lifting work necessary to close gaps rapidly

There are others as well, but these are major ones. Perhaps the best way to express what we believe is necessary within a large corporation to elevate practices uniformly across the entire enterprise is shown in Figure 6.

It shows a wide variation of maintenance spend across a fleet of plants in a typical corporation (shown by the light curve). The goal, in our view, is to reduce the variation in the corporation (shown by the dark curve). This would mean that there is less variation in performance from plant to plant, and, presumably, the level of performance is elevated beyond what it could be by simply attacking the opportunity plant-by-plant.

It should be again noted that we know of no company in existence today that has achieved uniform elevated levels of reliability performance across the entire enterprise—fleet-wide. Several companies are vying for this distinction and the business performance that will come if this is achieved.

What are the benefits of seeking outside assistance?

As was mentioned in the previous section, one of the impediments to success is failure to recognize the need for specialized expertise and experience from outside the company. Expressing this in a positive way, it is a very consistent practice among the top performers to employ outside assistance. In fact, we have yet to encounter a single company recognized as a leader and top performer in asset management that does not credit some of their success to a few strategic partners. There are several reasons why outside assistance can be particularly beneficial:

1. Overcoming Myopia

It is often difficult to assess our own shortcomings and weaknesses objectively. Conversely, we may tend to overestimate our strengths. While the role of an outside party is not to curb enthusiasm, it can provide a more realistic assessment of a company's performance relative to its industry peers. An outside entity can usually bring a more accurate appraisal of a company's reliability performance than can be achieved from the inside out.

2. Time to Results

The longer it takes to assess reliability practices and implement necessary improvements, the greater the likelihood that a company will lose focus and incentive to change. While speed alone is not the only determinant in program success, the ability for an outside party to tackle reliability as a defined "project" has proven time and time again to be helpful in getting companies to their goals than when employing a purely "do it yourself" approach. It is important to note, however, that reliability is not something that is "outsourced." The goal of any project is to create a sustainable program that fully involves the customer at every step so that it is the customer's program—not the consultant's.

Another aspect of this is related to resources. Most companies do not have an abundance of resources to allocate to a reliability project. They still have their "day jobs." An outside entity can provide the vital resources to "get stuff done" by providing the engineering, technology implementation, and other tasks necessary to build and implement a reliability program that can then be easily transitioned to the customer's day-to-day work practices.

3. Experience

An outside party brings the benefit of experience that crosses many disciplines and industries. Typically, they've seen the same problems over and over again and have been trained to not just identify them, but correct them. An entirely do-it-yourself approach often destines a company to reinvent the wheel, typically at great expense in terms of both money and time.

Admittedly, the concept of a "consultant" often has negative connotations. They waltz in, make their recommendations, waltz out, and have no ongoing stake in the business or in implementing their suggestions. When choosing an outside party to work with, a key area to examine is their ability to work beyond the assessment and recommendation phases, and assist with the implementation, cultural change, and program maintenance phases. When a consultant is actually required to put their recommendations into practice, there is typically a much higher likelihood that their recommendations will be practical, will reflect the realities of the business environment, and will result in project and program success.

Changing Results, Not Just Activities

At the end of the day, reliability is about business results. If "changing the game" simply means different activities without correspondingly different results, it isn't really changing the game at all. Fortunately, there is an abundance of success stories—some quite dramatic—that attest to the effectiveness of reliability in its ability to transform business results, not just business activities. We provided two such examples of companies that were able to "change the game" through changing their approach to reliability at the beginning of this article. In our experience, these are not isolated examples that only a few companies can hope to achieve. Instead, they represent the benefits that are readily available to any company willing to seriously apply a rigorous and holistic reliability approach to their operations and maintenance activities. ▣

When one event is one too many...

Jeanne Fallon-Carine
EHS Leader, Optimization and Control
GE Energy
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Our General Manager for services, Jim Junker, probably summed it up best: "In the industries we serve, you either demonstrate that you can perform the work safely, or you become a potential liability issue for our customers. In short, you don't get invited back. It's that simple."

Our customers understand that just one Environment Health and Safety (EHS) "event" is one too many. When something goes awry in a plant, the public and the media generally don't distinguish whether it was the plant's own employees or contractors—the plant takes the brunt of the criticism. It only takes a second to erode years of credibility and good will for our customers and ourselves.

That's why at GE, EHS is more than just a fundamental responsibility to our employees and shareholders—it's a smart business practice that adds value to our customers by protecting their reputations as well as our own. Our goal is to continue to improve availability, job efficiency, and the time it takes to get your equipment back into service.

To ensure that GE Energy is delivering against your EHS expectations, we take a proactive approach. Our service team works with each customer's EHS team through pre-qualification programs, job risk assessments, and on-going audits and inspections to ensure that our team, and our subcontractors, follow a site's EHS program and meet customer goals and expectations.

Our teams are devoted to finding ways to better meet customer needs. Looking for synergies and ways to eliminate redundancy for processes, procedures, and training can reduce costs of compliance while maintaining a high level of performance and quality. Streamlining our internal EHS processes is another mechanism that simplifies doing business with GE Energy. We are developing consistent EHS policies and training requirements and implementing a single safety risk assessment tool. Our services businesses are focused on delivering simple, safe, and efficient services for you.

Another aspect of our approach involves proactive EHS meetings with our customers. These meetings are a platform to reinforce our EHS commitment and to gain insight around our customer's EHS needs and expectations. In many instances, we have teamed with customers to have best management practice sharing sessions. Using technology like digital training, computerized audit tracking, and action item closure reporting to drive EHS ownership throughout our operating teams has resulted in proven EHS performance that is significantly better than industry norms.

Our Business Continuity and Pandemic Planning efforts are a recent example of proactively delivering customer value. One of the top priorities at GE Energy is maintaining the continuity of our operations while protecting our employees and customers around the world to ensure that we can continue to meet our customer's critical needs in the event of a crisis. We recently performed a business wide review and enhancement of our Business Continuity Plan and crisis management preparedness. The goal was to ensure that our business is adequately prepared to respond to crisis such as a pandemic outbreak of the avian influenza. We tested our current plan and updated it to address the unique concerns and challenges that would be associated with a global crisis.

The plan covers critical areas such as:

- Critical business and IT systems identified, potential failure modes assessed, contingency plans established
- Global traveling—considers border closures, breakdown of public transportation and quarantines
- Global communication plans and networks, covering local and distributed workforce
- Succession and delegation of authority including backup of key functional and business leadership
- In-depth evaluation of mission critical suppliers and their preparedness status
- Work-from-home capability and remote access to key systems and data
- Significant and extended absences (20-50%); illness prevention and response
- Pandemic preparedness

That's the difference—working together with our customers to add value by making safety and environmental compliance integral to everything we do for you.

GE
Energy

Save the Dates!

Four Upcoming Conferences for Users of Bently Nevada™ Asset Condition Monitoring and Our Optimization and Diagnostic Software

Building on our successful User Conferences in Atlanta and Dubai in 2006, we're pleased to announce additional conferences in 2007 for our worldwide customers:

- Amsterdam, Netherlands – March, 2007
- Dubai, UAE – April, 2007
- Houston, TX – July, 2007
- Singapore – August, 2007

Topics will include condition monitoring, System 1® software, plant performance and optimization software, and plant supervisory control optimization.

Future issues of ORBIT will provide more details for these events as the dates grow closer, along with additional venues for our series of 2007 User Conferences.

imagination at work

Understanding $\sqrt{k/m}$

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Editor's Note: *The concept of a system's natural frequency is absolutely fundamental to every aspect of machinery diagnostics and rotor dynamics. In this excellent article, the author reviews the basic relationships between rotor mass, rotor stiffness, and natural frequency of vibration by way of a brief refresher on the topic. This is supplemented by a case history that deals not only with the relationship between stiffness and mass in observed vibration frequencies, but highlights another frequently encountered but often overlooked problem in the field: excessive axial vibration in a support structure.*

A simple oscillatory system consists of a spring and mass as shown in figure 1. The mass attached to a vertically oriented spring will cause the spring to be extended downward to the equilibrium position y_0 with the amount of deflection being proportional to the weight of the attached mass. Application of Newton's 2nd law to the vertical spring-mass system yields

$$mg = ky_0 \qquad [1]$$

where:

m is the mass attached to the spring;
g is the acceleration due to gravity;
k is the spring constant; and
y_0 is the equilibrium vertical position of the mass **m**.

If the mass is displaced from its equilibrium position and allowed to freely oscillate, its motion can be described by the expression

$$y(t) = y_0 + A\cos(\omega t + \phi) \qquad [2]$$

where:

y is the vertical position of the mass as a function of time;
y_0 is the equilibrium vertical position of the mass;
A is the amplitude of motion;
ω is the angular frequency;
t is time; and
ϕ is a phase constant.

Further manipulation of the expression yields the commonly seen solution for f_n, the natural frequency of oscillation of a simple spring mass system

$$f_n = \frac{1}{2\pi}\sqrt{\frac{k}{m}} \qquad [3]$$

which simply states that the natural frequency is directly proportional to the square root of stiffness and inversely proportional to the square root of mass.

This is intuitive to anyone that has observed a stringed instrument such as a piano, violin, or guitar. The larger strings have more mass and vibrate at lower frequencies compared to the smaller strings. Larger mass = lower resonant frequency. Likewise, as a string is tightened (stiffness increased) the frequency increases. Larger stiffness = higher resonant frequency. Rotor dynamic systems are no different. If a rotor loses mass (such as through loss of a blade) it will show an increase in resonant frequency. If it decreases in stiffness (such as via a crack, loose support, or change in bearing clearance) it will show a decrease in resonant frequency.

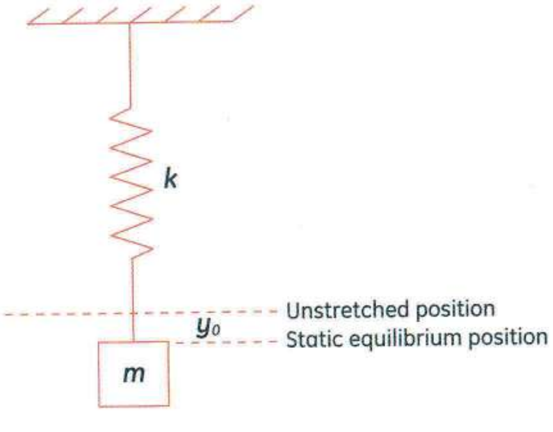


Figure 1 – **Simple oscillatory spring/mass system.**

Case History

Application of this $\sqrt{k/m}$ principle readily solved a problem recently encountered with a steam turbine generator machine train. The customer had experienced an oil leak at the pedestal bearing that provided support at the outboard end of the exciter. This pedestal bearing, manufactured of fabricated steel plate, also acts as a reservoir for the lubricant. Subsequent to the repair of the pedestal, it was decided to monitor the vibration of the pedestal using seismic transducers in an effort to investigate the root cause of the failure of the weld.

Very high vibration was experienced in all planes of measurement, but most notably in the axial direction where the amplitude was in excess of 20 mils pp. It is believed that this axial vibration was the cause of the crack in the base of the support pedestal. Figure 2 shows the axial transducer trend plot as the machine was ramped up to 3600 rpm.

Examination of Figure 2 shows a very rapid escalation in amplitude beginning at approximately 3000 rpm.

Figure 3 is a 2X filtered polar plot acquired from the same transducer during ramp-up of the machine. If there is energy present at twice running speed, then a device will respond in resonance when the machine speed is at one-half of the resonant frequency. In this

(continued on page 48)

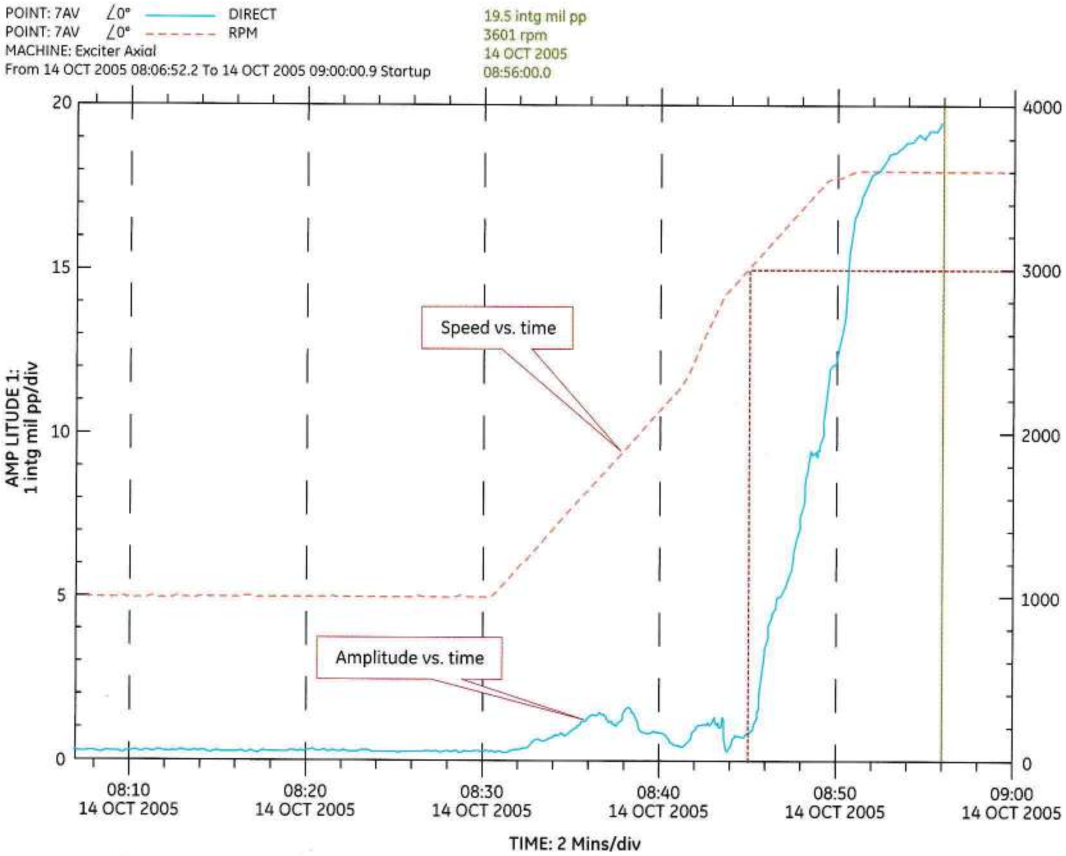


Figure 2 – **Trend plot of machine rotational speed and axial seismic vibration on #7 bearing pedestal.**

The Historical Development of $\sqrt{k/m}$

Editor's Note: *The following is provided courtesy of Dr. Neville Rieger, President of Environmental Energy Technologies, Inc. and the Chief Scientist and founder of STI Technologies located in Rochester, New York. Dr. Rieger is most noted for his extensive expertise in the dynamics of rotating machine components based on 38 years of industrial experience in the structural and flow analysis of turbo machinery, including several years with the Large Steam Turbine Division of GE in Schenectady, New York. Dr. Rieger has a deep interest in the historical development of vibration analysis and, in particular, the origins of the* $\sqrt{k/m}$ *formula.*

The critical aspects of our knowledge about vibrations we owe to Galileo, who in 1610 gave us the concept of mass; to Hooke in 1660 (and Marriott in 1660) who provided the concept of elasticity and stiffness; to Newton in 1665 (and Leibnitz in 1684) who gave us the calculus; and to Newton in 1687 who gave us the canonized laws of motion.

The first experimental studies of vibration were apparently those reported by Galileo in 1584, when he deduced the laws of the pendulum from the oscillations of a swinging lamp in the Pisa cathedral. In 1636, Mersenne studied the vibrations of stringed musical instruments from experiments on the oscillations of long ropes, and gave us the laws of string vibrations. Huygens (1659) contributed the idea of forced vibration from studies of pendulum oscillations driven by a clock escapement mechanism.

The dawn of vibration analysis came with Taylor's (1713) analysis of the vibrations of a continuous massive string. Taylor used Hooke's results and deduced an expression for the resultant force acting on an element of a string. He then applied Newton's momentum principle to find (from theory alone) that the formula for the lowest frequency of the string (in modern notation) is:

$$F = \frac{1}{2\pi}\sqrt{\frac{T}{\sigma}}$$

Taylor also gave us the idea of reducing a distributed mass to a point mass. This idea was again utilized by John Bernoulli (the father of the famous Daniel Bernoulli) in 1727, in his analysis of the transverse vibrations of a string, when he used Hooke's concept that the restoring force is proportional to the displacement. For the lowest mode, he gave the formula:

$$F = \frac{1}{2\pi}\sqrt{\frac{k}{m}}$$

Thus, John Bernoulli is the most likely originator of the famous formula. Bernoulli published his work in the *Comm. Acad. Petrop. Vol. 3* (1728), pp 13-28, (published 1732).

The foundations of vibration theory for continuous media were established between 1733 and 1735 by Daniel Bernoulli and Leonard Euler. Bernoulli had a clear understanding of the relationship between natural frequencies and modes in 1733. These two mathematical scientists, working in close collaboration (by letters between Basel and St. Petersburg) had, by 1734, correctly achieved the fourth-order differential equation for the transverse vibrations of a prismatic bar. By 1735, Bernoulli had suggested (and Euler had utilized this suggestion) to solve this fourth-order equation, once again using an infinite series approach. Their solutions were given as eigenvalue equations for several kinds of end conditions, which are common knowledge today.

Another great advance of this time was Euler's discovery in 1739 of the generality of the exponential method for the solution of differential equations with constant coefficients by a "superposition of particular solutions of the form e^{px}". This method was communicated in a letter from Euler to John Bernoulli (also in Basel), dated September 15, 1739 (referred to by C. Truesdall). This is the basic method of analysis that is used by analysts today to solve problems involving differential equations of linear systems. Euler continued his triumphs of those years by studying the oscillations of a pocket watch, suspended by a string from a support. The impulses from the escapement of the watch set it into pendulum-like motion. He expressed the forced motions of the watch by the differential equation:

$$M = \frac{d^2x}{dt^2} + Kx = F\cos(\Omega t)$$

It was the first time he used the frequency ratio (Ω/Ω_n). Thereafter, he discovered to his (apparent) surprise that this ratio represents a condition of resonance when $\Omega = \sqrt{k/m}$. He communicates this surprise in the above-mentioned letter to John Bernoulli (Truesdall). Euler made several additional discoveries in this field during the years 1739—1749 and after. Many other famous contributors followed Euler during and after this brilliant period—Daniel Bernoulli, Jean D'Alembert, and the great generalizer James Lagrange. By 1789, the field of vibration of simple systems had been thoroughly explained, leaving only 2- and 3-D continuum systems for analysis in the 19th century. Lagrange completed this great early period of vibration analysis with the publication of his famous book *Mechanique Analitique* in 1789, in Paris, on the eve of the French Revolution.

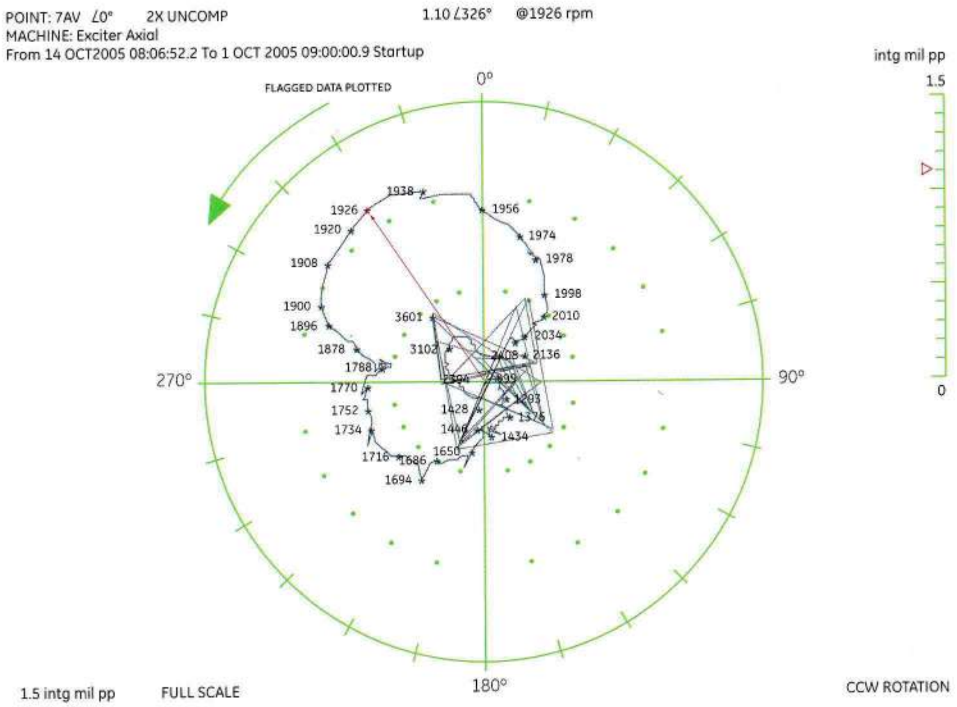


Figure 3 – **2X filtered polar plot on the #7 bearing axial plane.**

(continued from page 45)

case, when the machine is at approximately 1926 rpm, the polar plot shows classic symptoms of resonance. Since the plot is filtered to the 2X component, this identifies the resonance as approximately 3850 rpm, approximately 5.5% above the normal operating speed of 3600 rpm. This technique can be utilized to identify a resonance that is normally above the operating speed of a machine. Although it fails to account for stiffening due to gyroscopic effects, the technique often proves to be highly useful in resonant frequency identification.

A test run was accomplished with additional mass on the pedestal to see if the resonant frequency could be lowered, thus shifting it away from the 3600 rpm operating speed. With several bags of sand on top of the bearing pedestal, the amplitude fell to approximately 7-8 mils pp in the axial direction. This simple test confirmed that the resonance would indeed respond to efforts that would shift the resonant frequency away from the operating speed.

It was not deemed practical or expeditious to modify stiffness of the support. As such, a crude mass consisting of 250 lbs. of plate steel and lead sheet was affixed to the upper half of the bearing. The mass was affixed via the drilled and tapped hole normally utilized for a lifting lug. Figure 4 shows the arrangement of the applied mass.

Figure 5 shows the startup and shutdown trend of direct (unfiltered) vibration on the #7 bearing (axial plane) with the added mass. Note that Figure 5 is scaled identically

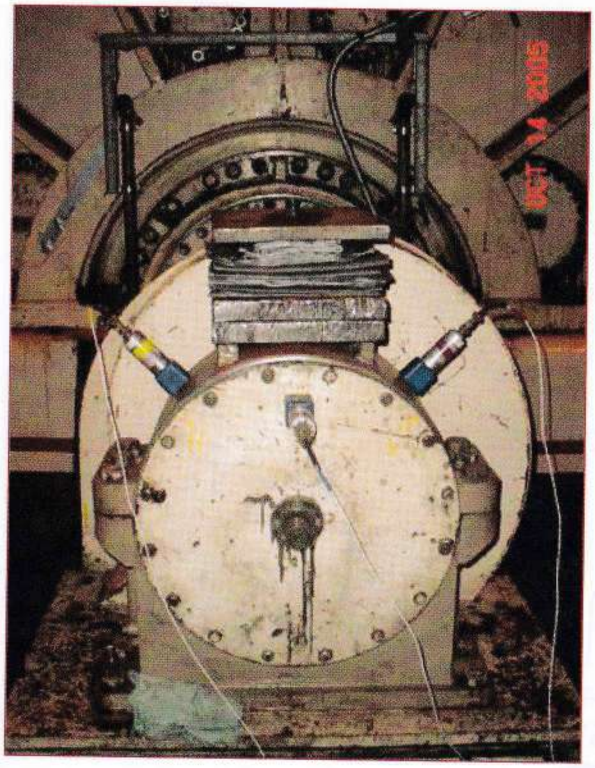


Figure 4 – **250 lb. mass applied to top of bearing #7 (enclosure removed). Note temporarily affixed seismic transducers in X-Y radial planes and axial plane.**

to the former Figure 2 to permit direct comparison of amplitudes. Significant reduction of amplitude was obtained by the mass addition. With the mass addition, the axial vibration was approximately 1 mil pp at running speed. The maximum direct amplitude in the axial direction during ramp-up was slightly less than 6 mils. Additionally, all other measurement planes gave vibration below 1 mil pp.

Figure 6 shows the Bodé plot of the axial transducer during startup and shutdown. The resonance is now at approximately 2500 cpm and exhibits a 1X-filtered amplitude of approximately 4-5 mils pp. At synchronous speed, the 1X amplitude is approximately 1 mil pp.

> **"SIGNIFICANT REDUCTION OF AMPLITUDE WAS OBTAINED BY THE MASS ADDITION."**

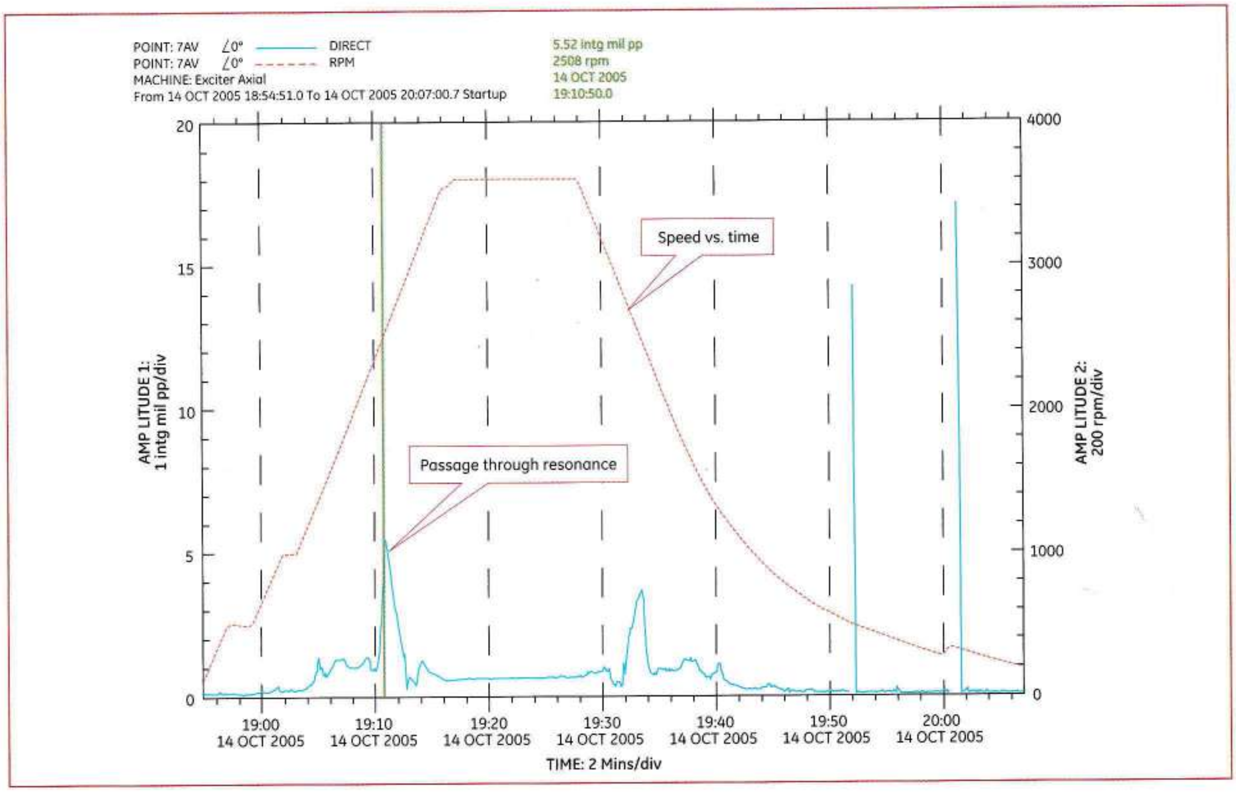


Figure 5 – **Trend plot of machine rotational speed and axial seismic vibration on #7 bearing pedestal (with added mass).**

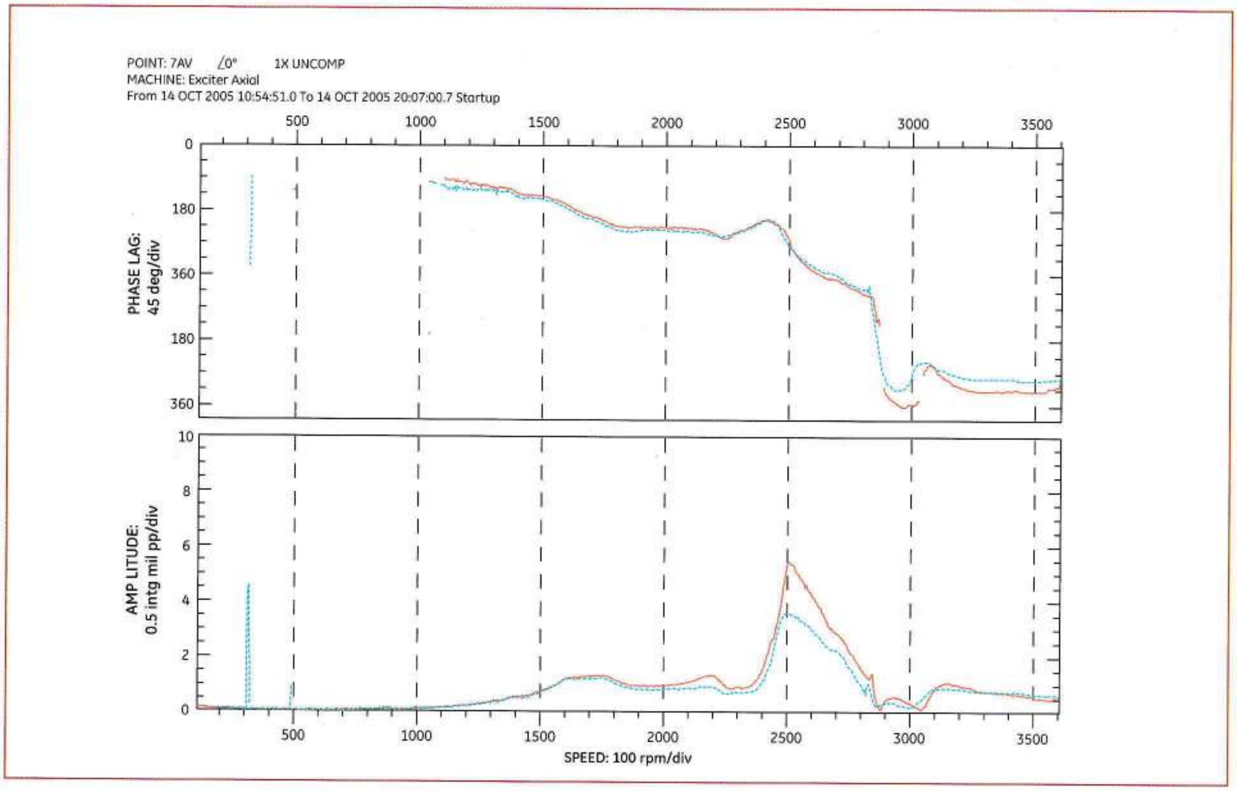


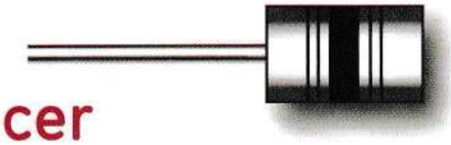
Figure 6 – **Bodé plot of axial seismic vibration on #7 bearing pedestal. Startup is indicated by the solid red line and shutdown by the dotted blue line.**

Conclusion

The resonant frequency of rotor dynamic systems is a function of both stiffness and mass, and this relationship is highly useful when diagnosing problems. For example, comparison of a baseline Bodé plot with a later Bodé plot showing a decrease in resonant frequency would signify that the rotor dynamic system had either increased in mass or decreased in stiffness. For some machines, an increase in mass will be consistent with operating conditions that allow a build up of material on the rotor, changing its resonance and balance conditions. For example, this is commonly encountered on centrifuges. For other machines, an increase in mass is not likely, balance conditions have not changed and decreased stiffness is the explanation, as demonstrated in the case history.

In addition to its usefulness in diagnosing problems, the mass/stiffness relationship is also useful for correcting problems. In the case of the centrifuge mentioned above, the problem is remedied by cleaning the accumulated build-up from the rotor (removing mass). In the case of insufficient stiffness, the remedy was to not only repair the cracked weld, but to also add mass to the bearing pedestal because implementing additional stiffness was not practical. This shifted the resonant frequency downward, further away from the machine's operating speed, dramatically reducing the vibration in the axial direction as well as all other measurement planes.

Thus, while the $\sqrt{k/m}$ relationship is one of the simplest tools available to those performing machinery diagnostics, its importance and application make it an extremely useful tool.



Cylinder Pressure Transducer Installation Pitfalls

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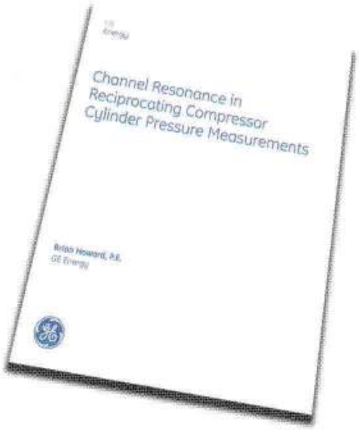
Cylinder pressure measurements are at the heart of effective condition monitoring for reciprocating compressors. Such transducers provide the all-important pressure-volume (PV) measurements needed to assess mechanical and thermodynamic performance of the cylinder and other parts of the machine. Since this is the part of the machine where compression actually takes place, accurate information is vital in order to ensure the machine is operating with maximum efficiency.

The single most common problem encountered in the field is improper installation of these transducers. When not installed correctly, pressure resonances can occur across the face of the transducer, leading to a transducer output that is completely overwhelmed by the high-amplitude resonance response. The effect is similar to blowing across the mouth of a bottle to create a musical note. If blown just right, the bottle will resonate, often quite loudly.

An in-depth applications note (GER-4273) has been developed to assist users in understanding this phenomenon and in designing a proper installation to preclude resonance problems. You can request a copy of the application note using the reader service card attached to this issue of ORBIT and at www.ge-energy.com/orbit, or by contacting your nearest sales professional. **O**



Channel Resonance in Reciprocating Compressor Cylinder Pressure Measurements

Brian Howard, P.E.
GE Energy

Oldest Monitor Contest Winner

In the December 2005 issue of ORBIT (2005 Vol. 25 No. 3) we asked our readers to submit photos of the oldest Bently Nevada™ monitor still in use. The winner was Mr. Bill LaRowe, a Sr. Technical Support Engineer with Atlas Copco. Although Atlas Copco supplies our most current monitoring systems with their new machines, they still have several Bently Nevada™ 1700 and 5000 series self-contained, panel-mounted monitors dating back to the early 1970s that see occasional test bench use. In Bill's words, "We actually still sometimes use the monitors, but mainly only to power Proximitor® transducers or verify shaft runouts. With the BNC connector on the 5000 series we can connect easily to a spectrum analyzer in test situations. Admittedly they are not used much any longer, but they do still function well."

The prize? A $1500 training voucher was sent to Atlas Copco, redeemable for any Bently Nevada™ training course offered by GE Energy.

Frankly, we were relieved to know that the "oldest" monitor was being used for something other than continuous machinery monitoring and protection purposes. While we take tremendous pride in the quality of our products, we don't advise using technology that is 30+ years old for actively monitoring your machinery.

If you are relying upon older technology from us for machinery monitoring applications, we strongly encourage you to consider upgrading for at least three reasons:

1. Electronics age, drift, and wear out over time. Relying on these older systems to actively protect or monitor machines can result in false or missed trips.
2. These older systems do not provide the connectivity to modern software systems allowing more in-depth condition monitoring.
3. These older systems do not provide the connectivity to plant control and automation systems, effectively isolating plant operators from valuable machinery condition data and statuses.

Online Condition Monitoring Pays Off for INCO Limited

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Introduction

Inco Limited is one of the world's premier mining and metals companies, and the world's second largest producer of nickel. Based in Canada, the company has operations and an extensive marketing network in over 40 countries. Inco's world-class mineral reserve and resource base is among the best in the global nickel industry. Inco is also an important producer of copper, cobalt, and precious and platinum-group metals, and a major producer of specialty nickel-based products. The mining operation at Sudbury, Ontario, Canada is the largest fully integrated mining, milling, smelting, and refining complex in Canada, and one of the largest in the word.

Inco has three oxygen plants at its Copper Cliff Complex in Sudbury, and is expanding to a fourth, allowing it to continue to meet the substantial demands of the smelting furnaces, copper converters, and nickel refinery converters used in the operations there.

In the early 1990s, a 500 MM CDN expansion was performed, changing the smelter furnaces from reverb-style to flash-style designs. The expansion entailed the addition of new rotating equipment, including fans, blowers, and compressors. Technical specialists from Inco's Central Maintenance Department were consulted regarding their advice for condition monitoring instrumentation to protect these new assets and ensure reliable operations. After an extensive review encompassing all major manufacturers for such instrumentation, GE's Bently Nevada™ products were selected as Inco's standard. However, this exercise addressed only the new equipment as part of the plant expansion; existing equipment was not retrofit with monitoring at this time.

"THE PRODUCTION IMPACT, REPAIR COSTS, AND SAFETY RAMIFICATIONS WERE SUFFICIENT JUSTIFICATION...TO RETROFIT A COMPREHENSIVE MONITORING SYSTEM."

Failure Spurs Retrofits

The #1 oxygen plant utilizes a 6,000 hp compressor, per Table 1. The machine had been supplied in the 1950s, and at the time, it was not customary for the manufacturer to supply permanent vibration monitoring on such machines. Further, the machine had provided nearly 45 years of reliable service with regular maintenance intervals. As such, Inco had not perceived a need to retrofit the machine with a permanent monitoring system, although the maintenance department had requested such a retrofit in the early 1990s.

However, in 1995, a major machinery failure on this compressor severely impacted production and raised significant safety concerns, causing Inco to reevaluate the need for continuous monitoring. The mechanical problem had developed so rapidly that it was not detected in advance. Further, the failure liberated rotating components, sending them airborne. The production impact, repair costs, and safety ramifications were sufficient justification. Consequently, when the machine was sent to the OEM for repair, Inco elected to retrofit a comprehensive monitoring system consisting of X-Y proximity probes at each bearing along with several casing accelerometers on the gearbox. These were connected to a Bently Nevada 3300 series machinery protection system.

This failure spurred Inco to perform a review of all major pieces of equipments at the three oxygen plants, not just the affected compressor. This resulted in a decision to retrofit several other machines with 3300 monitoring systems and GE's Bently Nevada product installation team was retained to perform a turnkey project including disassembly of the affected machines, drilling and tapping holes to accommodate transducers, installation of wiring between the transducers and the monitoring systems, and installation and commissioning of Bently Nevada Data Manager® 2000 software. The complete system now monitors the major pieces of rotating equipment summarized in Table 1, and several site maintenance personnel and vibration specialists routinely review data in the system as part of Inco's condition monitoring program.

Table 1 – Equipment Included in Continuous Vibration Monitoring Program

Oxygen Plant(s)	Machine Type	Size
#1	Main Air Compressor	6,000 hp
#2	Main Air Compressor	12,000 hp
#3	Main Air Compressor	6,000 hp
1, 2, and 3	Cooling Tower Fans	≈100 HP

Case Histories

Case History 1 Avoiding an Unplanned Compressor Outage

The 12,000 hp main air compressor in the #2 oxygen plant (Figure 1) has been in operation since the early 1960s. The compressor is driven by a synchronous motor operating at 1200 rpm through a single-stage speed increaser with an output speed of 4946 rpm. A machine train diagram detailing the arrangement of bearings, couplings, monitoring system transducers, and assigned tag names is shown in figure 2.

In the mid-1980s, the original low-speed coupling was changed from a gear type to a rubber insert type, and the gearbox was also changed.

The high-speed coupling section has long been an area of particular concern on this machine. Two keyways, 90 degrees apart, are used to attach the high-speed shaft to the compressor coupling hub. Because the shaft is subjected to oscillating torsional forces on every start-up until the motor is synchronized and locked in to the electrical grid, these torsional oscillations eventually lead to excessive play in the keyways, resulting in shaft cracks.

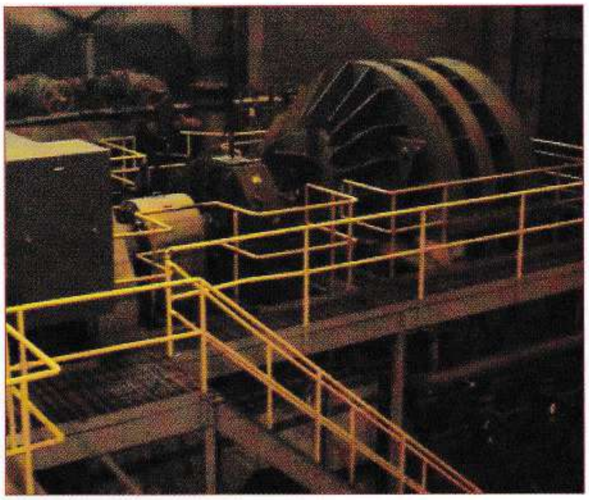

Figure 1 – **12,000 hp Main Air Blower for #2 Oxygen Plant.**

On September 14, 2004, after a routine shutdown to change a valve, the machine was restarted. This is shown in Figure 3 along with a disturbing development: comparison of vibration amplitude at the compressor inboard Y-probe before and after the shutdown shows a step change of 50%—increasing from approximately 1 mil pp to nearly 1.5 mil pp. Examination of several other probes along the train showed similar abrupt changes. The vibration amplitude stayed fairly constant for the next two days, but then began rising again, exceeding the alert alarm limit at around 15:00 on September 16th. Although the unit was still running well below its danger (trip) alarm setpoint of 2.47 mil pp, it was strongly suspected that some kind of mechanical abnormality was occurring since there had been no change in operating conditions to explain the change in vibration.

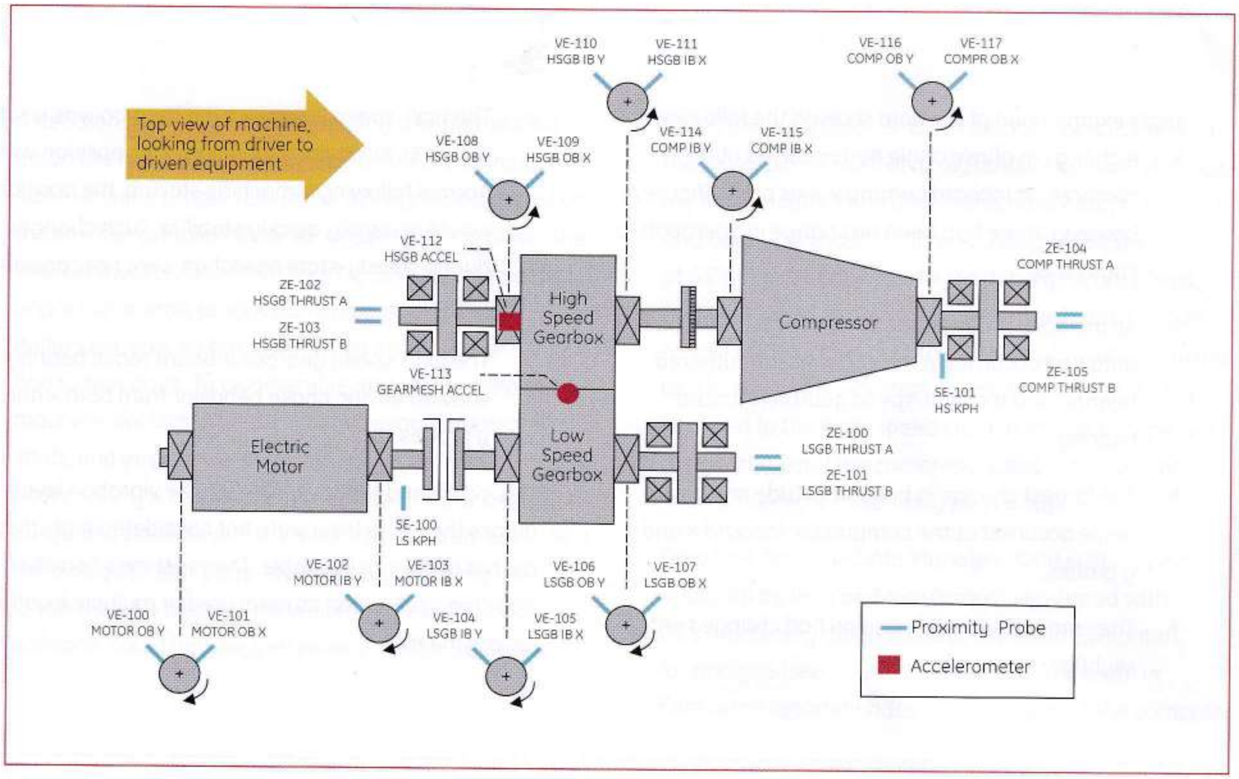

Figure 2 – **Machine train diagram showing bearing and transducer arrangements.**

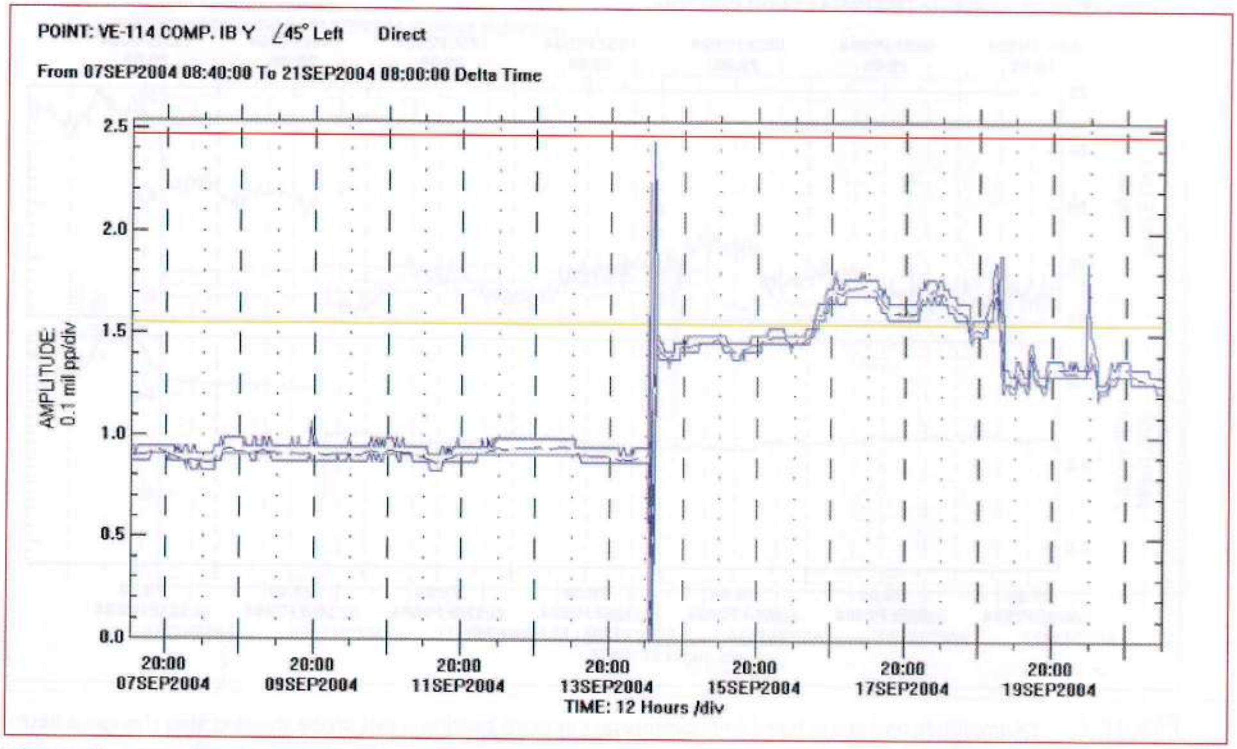

Figure 3 – **Overall vibration trend from compressor inboard bearing y-axis probe showing abrupt step change and subsequent alert alarm on September 13, 2004, followed by steady-state vibration levels approximately 50% above normal.**

Inco's examination of the data showed the following:

- A change in phase angle had occurred at the compressor inboard bearing x-axis probe (figure 4): however, there had been no change in operation to cause this.
- An increase in amplitude compared with historic data had occurred at the compressor outboard bearing and the high-speed gearbox inboard bearing.
- The largest change in both amplitude and phase angle occurred at the compressor inboard x and y probes.
- The compressor axial position had changed only slightly.
- The high-speed gearbox axial position was erratic (figure 5). Although changes in axial position were normal following a machine startup, the position would generally quickly stabilize; such changes during steady-state operation were not considered normal.
- The high-speed gearbox inboard radial bearing showed erratic phase behavior from both x and y probes.

This confirmed that even though the vibration levels across the entire train were not considered high, they did not appear to be stable. The machine's condition had clearly changed as measured at multiple locations across the train.

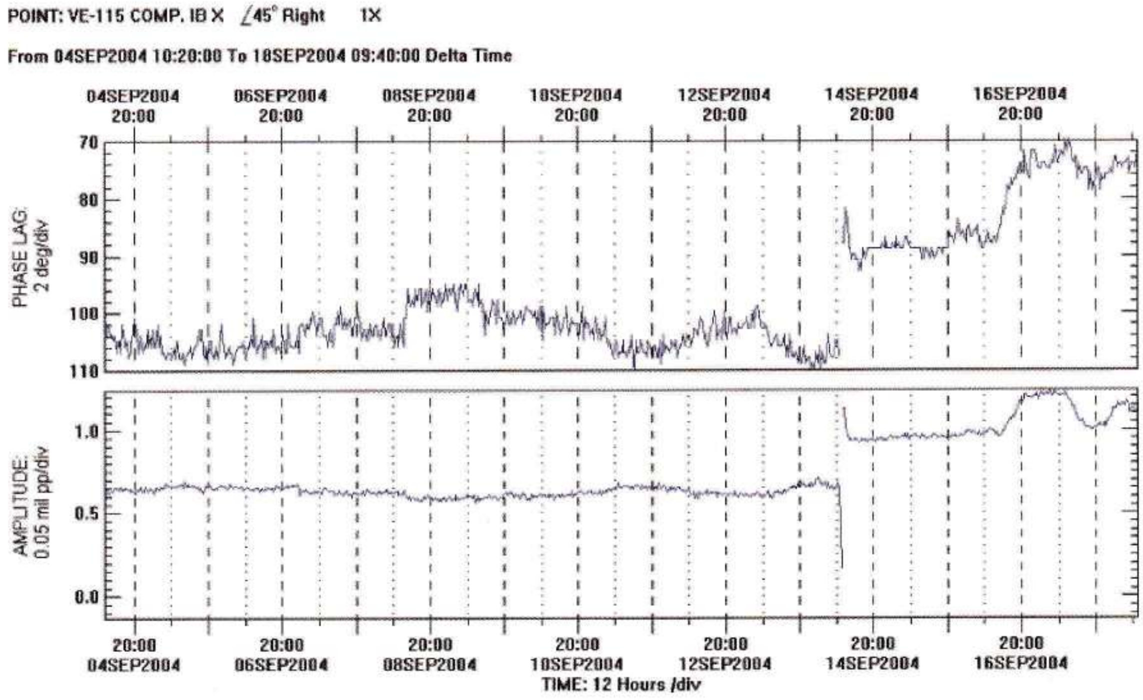

Figure 4 – **1X amplitude and phase trend from compressor inboard bearing x-axis probe showing step change in both on September 14, 2004, coinciding with shutdown/restart for a routine valve change. Abrupt phase changes can be particularly significant indications of a machinery problem.**

A decision had to be made regarding whether to shut down the machine for inspection or keep it running. At stake was the production of the #2 oxygen plant and of the smelter complex. If the #2 oxygen plant is down, the smelter must reduce feedstock by 33%, creating a major impact on metals production at a cost of millions of dollars per day. A shutdown would last anywhere from two to four days. To disassemble and reassemble the machine, perform non-destructive examination of the shaft, and inspect the coupling would require two days. However, if the downtime exceeded 48 hours, a plant purge and possible defrost would be required, extending the outage to four days. Alternatively, allowing the unit to run risked a total failure, which, in the worst-case scenario, could halt oxygen production for 56 weeks.

Given the magnitude of the financial repercussions on the plant, all avenues of analysis were consulted including Inco's engineering and maintenance staff, the OEM, and Bently Nevada™ machinery diagnostic specialists at GE's Edmonton office. All machinery records, history, and vibration data were reviewed. Due to past occurrences of shaft cracks at the unit's high-speed coupling, and because the vibration anomalies were primarily confined to the high-speed shaft in the section between the gearbox and the compressor, another crack did indeed seem the most likely possibility.

Data files from the Data Manager 2000 system were analyzed by Inco and simultaneously shared with GE's machinery diagnostic specialists in Edmonton for analysis (see sidebar on page 60). The team in Edmonton recommended an inspection of the compres-

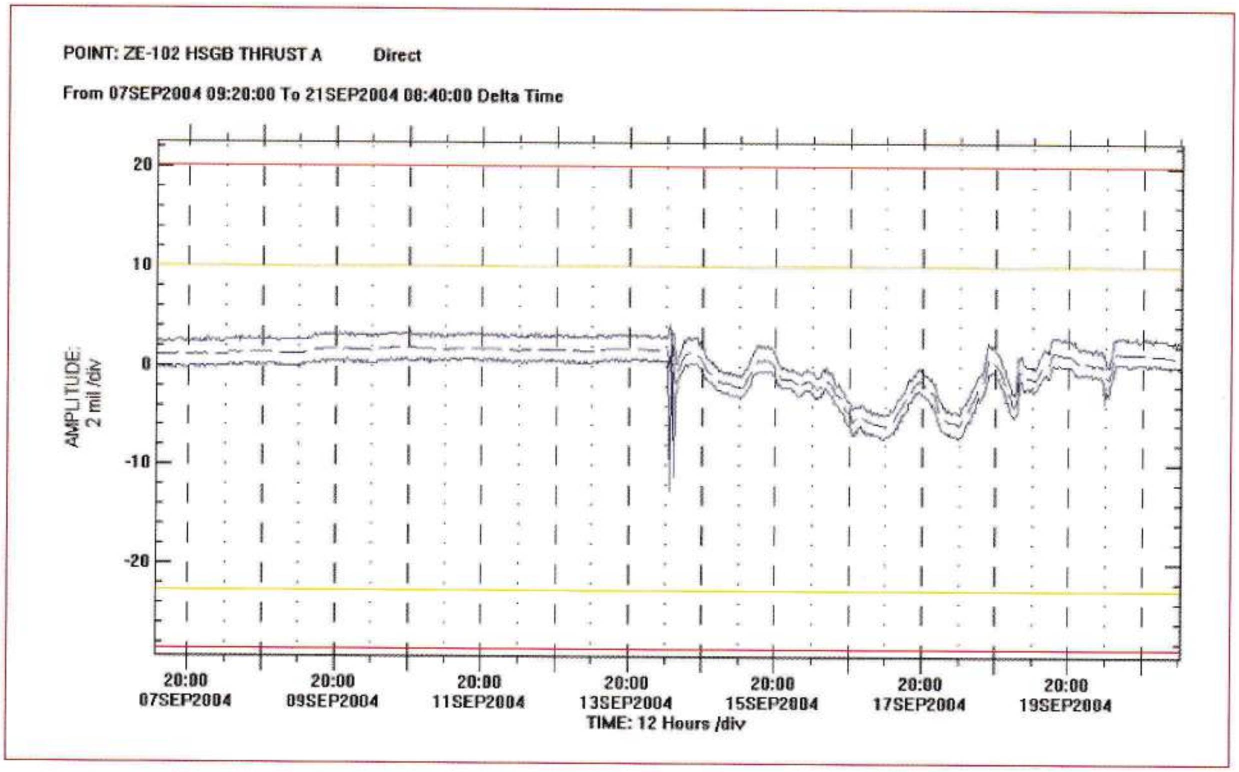

Figure 5 – **Axial position trend for gearbox high-speed shaft showing erratic behavior following shutdown/restart event on September 14th. Note highly stable behavior prior to shutdown/restart.**

sor inboard end shaft and impellers to determine the cause of the change in mechanical condition; they also suggested that shutdown data be collected to assist in determining runout and mass unbalance severity. Because shutdown data had been collected in previous years, the newly collected shutdown data would allow for comparison. A shaft crack would be expected to create a reduction in stiffness, lowering the resonant frequency. Comparison of current and historical Bodé plots would clearly show this, helping to confirm or rule out a cracked shaft diagnosis.

Because a restart of the unit would subject the unit to transient torsional forces that might exacerbate the suspected cracked shaft, the plant elected to forego an unplanned shutdown and wait for a planned outage instead. When the planned outage eventually occurred, transient data was collected and analyzed. However, comparison of historical (Figure 7) and current (Figure 8) Bodé plots showed very little change (6%) in the rotor system's natural frequency along with almost no change in amplitude or phase angle at resonance. A cracked shaft will typically result in a lowering of resonant frequency by at least 20% along with significant phase (and sometimes amplitude) changes at resonance. Thus, the transient data suggested that a shaft crack was not likely the problem.

With shaft crack highly unlikely based on the most recent data collected, focus was narrowed to the high-speed coupling. The general consensus was that the coupling was experiencing lock-up. Unlike the rubber insert design of the low-speed coupling, the high-speed coupling utilized a wet lubricated gear-type design with a typical life span of 5-10 years. Since Inco's coupling had been in service for 15 years, it seemed likely that the coupling was simply worn out. Cost for a new coupling was approximately $20,000, but came with a lead time of four months. To get a new coupling in place faster, Inco decided to pursue installation of a different coupling design that was available immediately from

Database Transmission Versus Plot Transmission

One of the features Inco cites as most useful in their condition monitoring software is the ability to export all or selected portions of the database for analysis by others, such as the machinery OEM or GE's Bently Nevada machinery diagnostic specialist team. This capability allows the recipient to load the data into their own copy of the software and generate plots and data presentation formats of interest. According to Pat Wozny, Sr. Specialist of Inco's Central Maintenance Vibration group, this is considerably more useful than simply e-mailing plots back and forth. "There is so much rich data contained within the database that e-mailing every possible plot of interest is very inefficient. And even if you e-mail the right plots, the recipient may want to zoom in on portions of the data and cross reference trend plots with dynamic data plots. Because we can export the actual database, this saves considerable time and allows the recipient of the data to look at everything of interest. It eliminates the need to iterate plots back and forth and it keeps us from being a bottleneck when the data recipient needs to drill down and look at things in more detail." Wozny also likes the system's ability to export only relevant portions of the database. "The database can be huge so we especially value the ability of the software to selectively export only the data of interest, such as the events immediately leading up to and following a shutdown."

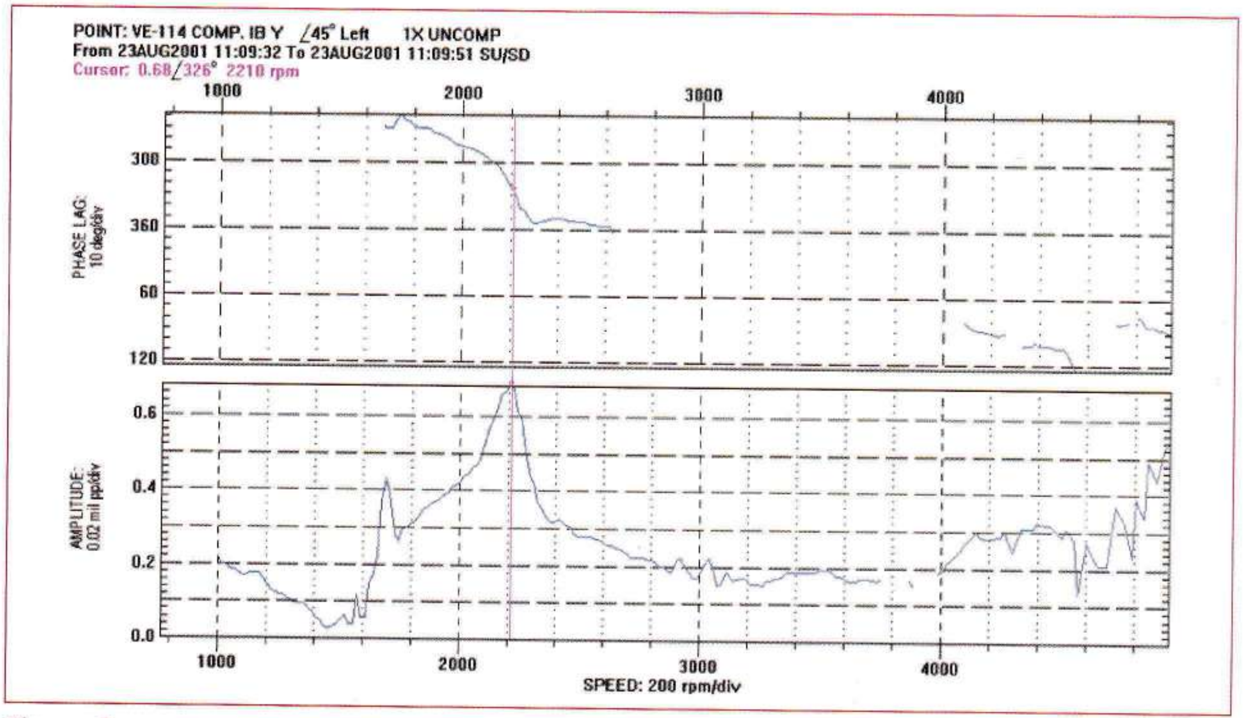

Figure 7 – **Baseline data collected in August, 2001 at compressor inboard bearing Y-probe. Cursor position shows rotative speed, amplitude, and phase at resonant frequency.**

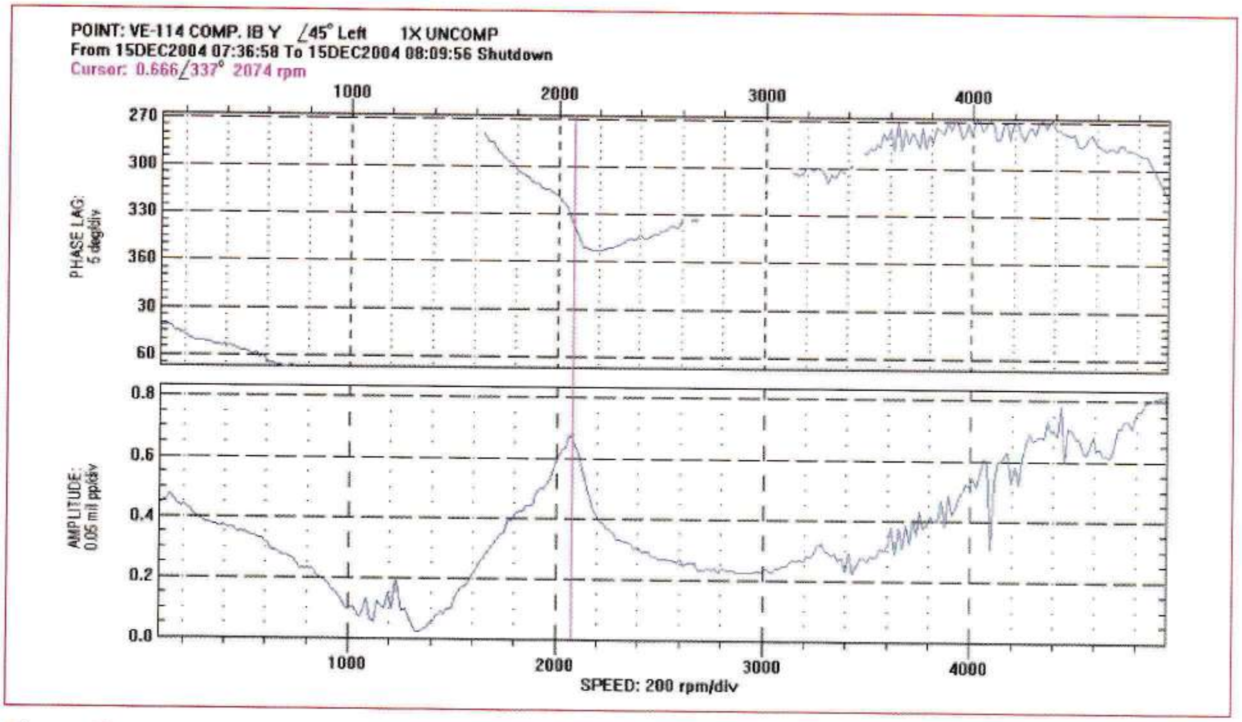

Figure 8 – **Bodé plot collected in December, 2004 showing only minor changes in resonant frequency, amplitude, and phase (as noted by cursor position) when compared with baseline data of Figure 7. This strongly precluded the likelihood of a cracked shaft.**

the supplier. However, a change of coupling type necessitated a thorough engineering analysis and would not be supported completely by the manufacturer without extensive finite element analysis. Both of these represented a delay in the immediacy of replacement.

While this engineering analysis of a new coupling type was underway, an unexpected event occurred. The plant operators had shut down several cooling towers that were linked to the compressor's lubrication system intercoolers. Consequently, the oil temperature to the high-speed coupling increased. At the same time, the bearing vibration reduced and stabilized. Without the immediate vibration data feedback that the Data Manager 2000 system provided, this event would have gone unnoticed. Instead, the Data Manager 2000 system not only alerted personnel to the correlation between oil temperature and vibration, it allowed them to experiment with different oil temperatures in an attempt to further lower the vibration. After some manipulation of the lubricant temperature, an optimal setting was found. With these lower vibration levels, the site abandoned the plans to switch to an alternative coupling type and elected to continue running the compressor at full capacity, closely monitoring the machine while they waited the four months for parts to arrive for the existing coupling. During the waiting period, the machine sustained at least 10 more starts and stops due to power failures or other circumstances necessitating brief shutdowns.

In every instance, the Data Manager 2000 system collected transient data, which was analyzed for change. The data showed no changes that would preclude a startup, instilling confidence that safe operation of the compressor could continue. When the coupling was finally replaced, badly worn teeth were revealed. Following replacement, vibration returned to its original baseline values.

The monitoring and diagnostic information provided by the Data Manager 2000 system was indispensable in allowing Inco to keep this machine running with confidence. Equipped with relevant machinery condition information, the site was able to isolate the most likely source of the vibration changes, schedule repair while keeping the machine online, avoid an unnecessary shutdown and inspection, and prevent the business from needless exposure to higher risk as would have been the case without good machinery information. As a result, millions of dollars were saved.

Case History 2 Avoiding an Unnecessary Alignment

Prior to installation of Inco's Data Manager 2000 system, the site relied primarily on the advice of the machinery OEM regarding maintenance and repair. Now, the site uses its own condition monitoring information to make many such decisions, with excellent results. An example of this occurred in 2000 when the main air blower underwent routine repair. The contractor involved suggested a major change in the foundation to accommodate alignment, requiring a 4-day outage to make the modifications.

"WITHOUT THE IMMEDIATE VIBRATION DATA FEEDBACK THAT THE DATA MANAGER 2000 SYSTEM PROVIDED, THIS EVENT WOULD HAVE GONE UNNOTICED."

The Value of Dynamic Data

Another feature that Inco cites as extremely useful is the ability of their condition monitoring software to provide dynamic data plots and analysis capabilities. Dynamic data is the waveform data provided by the vibration transducers and is characterized by the full signal content including the complex frequency components that comprise the waveform. In contrast, static data is simply a measure of some aspect of the vibration at a moment of time, such as the amplitude or phase. Most trending systems are capable of only static data—not dynamic data.

The following analogy is helpful in understanding the difference. The frequency content of mechanical vibration signals is typically very similar to that of music or audio information. Thus, each pair of X-Y probes typically provides enough raw waveform data in 60 minutes to fill a 700 MB CD, just as a stereo audio CD holds about an hour's worth of music. If an audio CD contained only static data, it would simply be some aspect of the waveform (such as the volume) at a moment in time. Without the full waveform, you have no music. In a similar fashion, without vibration waveform data, it is impossible to fully understand the behavior of the machine.

It is this ability of the system to capture and analyze dynamic data that sets it apart from typical trending systems, such as the historians supplied with many distributed control systems. Figures 7 and 8 are key examples of how dynamic data was used to rule out a problem (in this case, shaft crack) that would not have been possible using only static trend data. Such scenarios are commonplace when diagnosing machinery problems, underscoring the usefulness of dynamic data.

With millions of dollars again at stake for such an outage, the Inco team wisely chose to assess the alignment condition themselves before agreeing to the modification. Thorough examination of the information provided by the Data Manager 2000 system showed absolutely no indication of misalignment with all bearings in good condition. Consequently, no foundation changes were made, a 4-day outage was avoided, and millions of dollars were saved. Continued monitoring of the machine showed normal behavior with no propensity toward misalignment problems.

Summary

Online condition monitoring has enabled Inco to make critical as well as routine operating and maintenance decisions with much higher confidence. On at least two occasions, such capabilities have been worth multiple millions of dollars, as illustrated by the two case histories in this article. During the first year of operation alone, Inco estimates that the savings they realized more than paid for their DataManager 2000 system. Each year since that time the system has continued to accrue savings and benefits, helping Inco remain a leader in its industry.

Oil Analysis 101

Part 2 of 2

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Editor's Note: *Part 1 of this 2-part article appeared in the July 2005 issue of ORBIT (2005 Vol. 25 No. 2). It dealt exclusively with the rudiments of lubrication analysis. Part 2 continues by discussing how lubrication and vibration measurements complement one another as part of a complete condition monitoring program, and outlines how to establish a lubricant analysis program.*

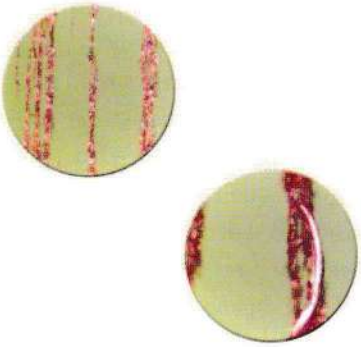
Introduction

Oil analysis has proven to be an ideal complement to vibration monitoring and is applicable to all oil-lubricated machinery. When a problem occurs in the oil-wetted path, oil analysis is more likely to pick it up early than vibration monitoring.

Oil analysis is particularly effective on equipment such as very slow-speed rotating machinery, and hydraulic systems where vibration monitoring capabilities may be limited or absent. It is also particularly effective on reciprocating machinery. However, don't conclude that these applications limit oil analysis, or that they are even the most important applications. It is often high-speed rotating machinery where oil analysis may be most valuable, despite the fact that vibration monitoring also is well suited for these machines. The two technologies provide insights that complement and reinforce each other so that a clear maintenance decision is possible for such machines—machines that are often the most critical in the plant.

Since oil analysis "sees" the machine from an entirely different perspective than vibration analysis, when the oil results confirm the vibration results, you can be more confident when taking specific corrective action suggested by the two analyses. Likewise, production managers find it difficult to say "no" to a shutdown with such clear evidence as a color photograph of large fatigue chunks, or cutting wear particles, especially when vibration readings are also confirming the problem.

(continued on page 66)



Case History – Oil and vibration help pinpoint a problem on a boiler feed pump

A power plant collected a routine oil sample from a boiler feed pump as scheduled. The lab analyzed the sample and reported high copper alloy wear (Table 1 and Figure 1). The customer then collected vibration data which showed multiple harmonics from an internal shaft-driven oil pump with amplitudes much higher than normal (Figure 2).

Based on corroboration of these measurements, the customer elected to take the unit offline for inspection, with particular attention to the internal oil pump. Inspection revealed a retaining nut on a steel worm pinion on the input drive shaft had worked itself loose, causing it to float erratically on the brass worm gear, thus producing excessive brass wear.

The problem was fixed and the unit was returned to service. A post-maintenance vibration check showed no evidence of further problems.

Table 1

Wear Metal (Coarse RFS)	Taken 3/17/97	Taken 6/17/97
Iron	0	1
Copper	0	58
Tin	0	6

Quarterly lab results showing abnormal copper alloy wear particles

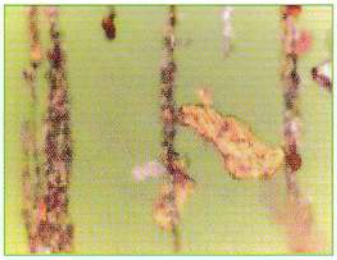
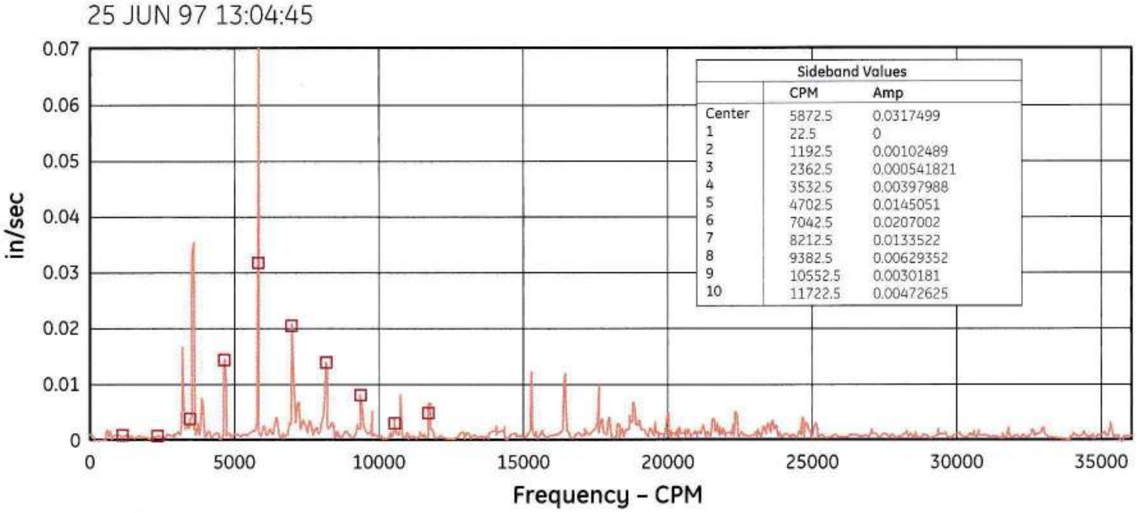


Figure 1 – Photograph of oil sample showing presence of copper alloy particulates.



Sideband Values

	CPM	Amp
Center	5872.5	0.0317499
1	22.5	0
2	1192.5	0.00102489
3	2362.5	0.000541821
4	3532.5	0.00397988
5	4702.5	0.0145051
6	7042.5	0.0207002
7	8212.5	0.0133522
8	9382.5	0.00629352
9	10552.5	0.0030181
10	11722.5	0.00472625

Figure 2 – Half spectrum plot showing high-amplitude harmonics of internal oil pump running speed.

"OIL ANALYSIS 'SEES' THE MACHINE FROM AN ENTIRELY DIFFERENT PERSPECTIVE THAN VIBRATION ANALYSIS...THE TWO TECHNOLOGIES PROVIDE INSIGHTS THAT COMPLEMENT AND REINFORCE EACH OTHER."

Establishing an Oil Analysis Program: Step-by-Step Guidelines

After your decision to include oil analysis in your predictive maintenance practices, the following nine steps are recommended to establish an effective program:

1. Identify the right machines for inclusion in the program.

All plant machinery should be categorized from a criticality point of view. What would be the consequence of a catastrophic failure of this machine? Is there a backup machine that can be used in the event of failure? How much downtime will a failure represent to the plant? To the machine? What are the lost production costs? Are there spares on the shelf? Are the parts standard or special-order, foreign-made or domestic? Answers to questions such as these will help you place your machinery into a criticality category. Perform oil analysis on all your most critical machinery at the outset, and be sure to give special attention to machines that are not good candidates for vibration monitoring. Then, add machines by category as you expand your program.

2. Gather essential information about each machine.

This includes information such as machinery description, unique ID number, lubricant type used, and type of bearings. Information about the metallurgy of the wearing parts is going to be necessary when abnormal wear is detected, but it need not be determined in advance. Of course, when you are setting up an oil analysis program, it is recommended to place as much information as possible into the lab database to assist in the diagnosis of abnormal conditions. Such additional information as sump capacity and filter specs can be most helpful to the lab analyst when recommending corrective action.

3. Visit each machine in the program to determine the best method of sampling.

Two methods are available: vacuum pump or sample valve. Install sample valves where possible to simplify taking samples, and to ensure that the samples are of the highest quality. These valves may be installed over a period of months. Some valve designs permit a quick connect and disconnect. The dead leg must be flushed prior to taking the sample. First install valves in machines where current sampling locations represent a safety hazard.

4. Chose a lab and have them set up a database with the information collected in step 2.

A testing "regimen" is agreed to for each machine; i.e., what oil analysis tests will be conducted. The regimen for a gearbox is different from the regimen for a steam turbine. Normally, the lab provides sample bottles, caps, labels (already filled in with unique ID#, machine description, and oil type as a minimum—you just add date, running hours or miles on lube, etc.), and shipping containers if appropriate. With the database ready at the lab, they can begin performing analysis as soon as the samples come in.

5. Sample and ship.

After each sample is taken and the label affixed to the bottle, the samples are packaged in a suitable cardboard box and shipped without delay. Individual bottles can be mailed in their cartons. Routine samples are usually shipped to arrive on the second business day. Urgent samples are more often shipped for next day delivery. The cost per sample for delivery is very small when a number are consolidated in the same box. It is a small price to pay for timely results.

6. Conduct test regimen.

When the samples arrive at the lab, each one is logged into the lab software, and a batch and lab sample number are assigned which will stay with the sample results. As each test in the regimen is performed, the results are fed automatically into the database. The data is trended, compared with norms or baselines, and a computerized status is presented to the analyst. This status either gives a clean bill of health or raises questions about lube condition, contamination, or machine wear.

7. Analyze the results.

The analyst must judge the results. If no abnormalities have been found, a status of "Normal" will be assigned and the analyst will go on to the next sample. If not normal, the analyst must then decide whether additional testing is required to determine the degree of the problem, and the root cause. After the additional testing is done (such as a Karl Fischer water or Analytical Ferrography), the analyst assigns a "Caution" or "Alert" status and adds a recommendation for corrective action. Conversations between the analyst and cognizant maintenance personnel are often necessary at this stage. All Caution and Alert sample results should immediately be reported by phone and fax, even when all the data is transferred electronically into the user's own trending software. In pinning down the root cause of abnormal results, it sometimes is necessary for the end user to provide additional information such as the type and metallurgy of the bearings, sump capacity, and other important factors that were not entered into the lab database originally. A form that lists all the pertinent information is provided by all commercial labs, but often not completed until problems are uncovered. For example, a lab obviously cannot determine the source of severe copper wear particles if the metallurgy of the oil wetted parts has not been described.

8. Conduct additional sampling if necessary.

The recommendation made by the analyst may be to take another sample right away, or to take samples upstream and downstream from the filter, or to look for a source of hard abrasive contamination such as a cap left off the oil fill in a dusty environment. When the number of particles suddenly increase in a machine oil sample, it could be contamination, a severe wear mode that has started, or a failed filter. Particle microscopic analysis will often help in discovering whether the mode of wear has turned from benign to severe. The job of the lab analyst is a difficult one and often entails working cooperatively with the end user to solve the problems found in the lab. A close working relationship is essential to gain the full benefits of oil analysis.

9. Archive the results.

Hard copy reports are being used less and less today with the popularity of electronic data transfer. This quick and efficient method of data transfer assures the user of better access to the data. Rather than being confronted with a stack of hard copy reports, end users can simply use their own computers and software to retrieve the most recent batch of sample results in alarm conditions. For users with integrated condition monitoring platforms, they can easily move between the vibration and oil data, getting the synergistic benefits of the two technologies for a more comprehensive condition monitoring picture.

Sampling

Taking the oil sample is critical, especially if the sample will be analyzed for coarse metal particles. These larger, heavy particles tend to settle out quickly and are more readily removed in the filter. Therefore, their distribution in a machine's oil system is not at all uniform. Taking the sample from the active oil stream, and in the same way each time, is essential for good trending results. The selection of the sampling point and method should be made with inputs from the lab. Each person who will take samples should go through a short course on taking samples. Most labs have specialists who will spend a day in your plant helping you select sampling points and methods, training personnel, and recommending special valves and sampling techniques.

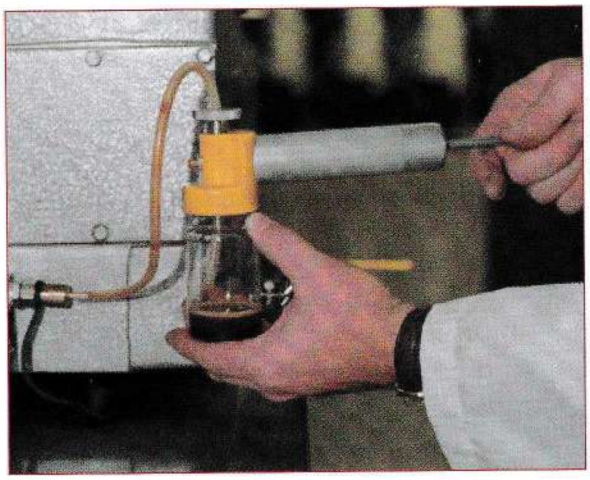


Figure 3 – **Using a vacuum pump and disposable plastic tube to collect an oil sample.**

There are generally three sampling methods used today:

1. A vacuum pump with disposable plastic tube (figure 3)

This is the most common way to take a sample from a non-pressurized sump. However, one must be careful to avoid taking a sample from an area of no flow, such as at a sump wall, or even worse, from the bottom of a sump where heavy debris settles and accumulates. A sample from the sump bottom will contain particles that are "ancient history" and are of no interest to the analyst. These old particles tell nothing about current wear and can only create false alarms for the analyst, requiring a re-sampling to dispel the alarm and confusion. For some difficult sumps, a custom made "dip-stick" is used with the vacuum pump. The plastic tubing is attached

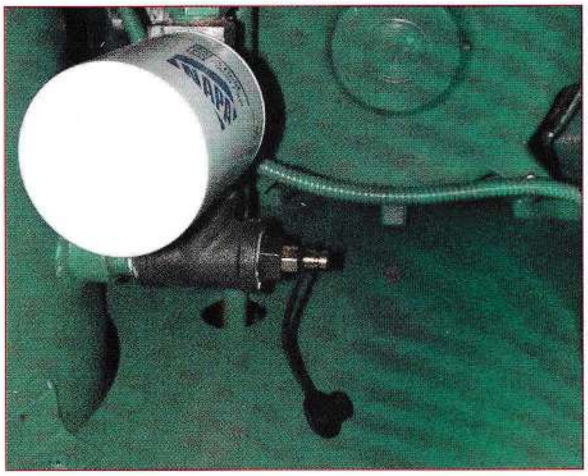


Figure 4 – **Oil sampling valve with protective cap removed.**

to clips on the dipstick and the dipstick inserted into the sump. The dimensions of the dipstick, the "stand-off", and its shape will ensure that the sample will be taken each time from approximately the same point, and away from the walls and bottom.

2. An ordinary valve

This method can be used to sample from a pipe or side of sump. However, care must be taken to flush out the stagnant oil leading up to the valve (sometimes called the "dead leg"), which is always present. This ensures that the sample contains the "live" lubricant actually circulating through the machine.

3. A special oil sample valve (figure 4)

This method can be used in the same places as method #2, and the same considerations apply. Some special sample valves have a spring loaded ball seat, which is unseated when a "needle" is inserted. The oil, if under pressure, flows through the needle and into the sample bottle. If no pressure is present, then a suction pump is used to "pull" the sample. These special valves come in different sizes and configurations, and can greatly increase the speed and convenience of taking a sample. They are particularly useful in dirty environments such as off-highway, highway diesels, mining, and dusty or dirty industrial sites.

Remember that the wear particles and contaminants are a separate phase in the oil and tend to settle out of the oil. Particles that are very small, on the order of 5 micrometers or less, stay suspended. These can be the only particles the lab sees if the person taking the sample does not capture a representative sample of the "working" oil in the system. Most labs do not test for metal particles larger than 5 micrometers anyway, unless they are using Rotrode Filter Spectroscopy. Some labs use the DR Ferrograph, which measures coarse iron. Thus, it becomes especially important to capture a representative sample if the lab is to measure the coarse metals. Without coarse metal analysis many severe wear modes will be missed.

"THE BIGGEST OBSTACLE TO THE ADOPTION OF OIL ANALYSIS AS AN EQUALLY IMPORTANT TOOL WITH VIBRATION MONITORING IS TYPICALLY ENTRENCHED CORPORATE THINKING."

Using Your Senses, Postmortems, and Quality

While using your common "senses" can be useful in detecting abnormal oil conditions, keep in mind that used lubricants are an identified carcinogen, and gloves should be used when handling used lubricants. Further, the smelling of oils should be avoided. Professional labs are strongly vented. Be careful!

Smell

Since a sample should be taken while the machine is running at some steady state, or shortly after shutdown, the resulting sample will be hot and any volatiles will often be evident to the alert nose. Even after the sample is received in the lab, volatiles attack the nearest nose when the cap is removed. Fuel dilution, freon contamination, and other chemical contaminants can be clearly identified by the smell.

Sight

Visually, you can also learn something, especially about the presence of water. Depending on the additives in the oil, water will sometimes quickly separate from the oil, so that you can see the water and oil separately if the sample bottle is clear plastic or glass. If the water forms a stable emulsion, the sample will appear milky or clouded.

Normally, wear particles and solid contaminants are not visible to the unaided eye—they are simply too small. However, when severe wear is underway the metal wear particles are sometimes large and plentiful enough to form a glittering deposit at the bottom of the bottle. Again, with a clear bottle, you will be able to see these particles. This event would be indicative of an ongoing severe failure mode.

Feel

With regard to feeling the oil by rubbing it between the fingers, the particles would have to be quite large (and therefore severe) to be felt.

Oil analysis may be used in a postmortem on a recently deceased machine, as a quality control test of a new-born machine, or it may be part of a predictive maintenance program for the periodic trending of the vital signs that machines are constantly generating. While use of these "life or death" terms is admittedly a bit dramatic, it does underscore that the decisions faced by industry often have significant financial and safety consequences. If you have ever asked a question such as, "Do we shut it down now and fix it over the weekend, or do we let it run and risk a catastrophic failure that could shut us down for three weeks?" then you understand the importance of making the right call. Oil analysis can provide the insight necessary to make the right decision.

Oil analysis also plays an important role in the testing and start-up of new machinery. The so-called "infant mortality" syndrome is well known. Errors in assembly, improper tolerances, blocked lubrication ports, and factory contamination can all work to cause the early demise of the newest and shiniest machine. For this reason, monitoring the oil condition for brand new machines and machines that have recently "crashed" is strongly suggested. However, routine, periodic oil analysis is no less valuable.

Overcoming cultural obstacles

The biggest obstacle to the adoption of oil analysis as an equally important tool with vibration monitoring is typically entrenched corporate thinking regarding lubrication and its testing. Most maintenance personnel, even those who are very sophisticated in vibration monitoring, leave oil analysis out of their predictive maintenance thinking, or at best put it on the margin. Instead, they tend to think of oil as the domain of the "the oiler." While the oiler's task is often to ensure that sufficient amounts of the correct lubricants are maintained in each machine, rarely are such individuals also responsible for determining the condition of the lubricant or the condition of the machine that it lubricates.

Instead, the lubricant supplier is often tasked with performing the oil analysis. Many times, the cost is quite attractive and may even be free. However, there are multiple problems with such an approach:

- An inherent conflict of interest exists in such an arrangement; the supplier's main objective is to supply lubricants, not to discover that the machine is failing, that the oil can continue to be used, or that the oil can be reclaimed by filtering and dewatering. When an independent lab is brought to the task, they can make unbiased recommendations.
- The testing is often not done on a regular periodic basis.
- The results are typically returned so long after the sample is taken that its significance is lost.
- The testing performed is mainly on the lube chemicals and physicals, with insufficient attention paid to monitoring contamination and wear of the machine itself.
- The results are not usually made available to the people who are doing the vibration monitoring.

Thus, while the cost of oil analysis supplied by the lubricant suppliers may be superficially attractive, there is often a "hidden" premium that is being paid by the loss of valuable information on machine condition and the ability to prolong the life of the lubricant. For all of these reasons, end users are usually best served by working with an independent oil lab, rather than their lubricant supplier. Indeed, the incremental benefits achieved from using an independent oil analysis lab will almost always eclipse the cost.

Summary

Oil analysis is a highly useful tool as part of a comprehensive condition monitoring program. It should generally be viewed as a complementary technology to vibration analysis where the two together are capable of assessing machinery condition better than either one alone. For some equipment, oil analysis will yield better results and is a better choice; for others, vibration analysis is preferred. The most proactive companies will assess their equipment based on criticality and failure modes, and then choose the appropriate technology accordingly.

Establishing an effective program is a systematic process and, using the steps outlined in this article, can be applied anywhere with good success. Finally, the benefits of using an independent lab typically far outweigh the cost savings of using a lubricant supplier's in-house lab and is a better choice in most situations.

Editor's Note: *GE Energy's services team is fully equipped to help customers establish and maintain a comprehensive, world-class lubricant analysis program. We also provide software compatible with a number of labs (including National Tribology Services) for archiving, trending, and analyzing lubricant condition. To learn more about these product and services offerings, contact the Editor.*